Faculté de Psychologie, Logopédie, et Sciences de l'Education

Is Resistance-to-Interference Domain-General or Domain-Specific? A Multi-Paradigm Investigation

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Disclosure

I, Coline Grégoire, declare that this thesis entitled *Is Resistance-to-Interference Domain-General or Domain-Specific? A Multi-Paradigm Investigation* and its data are original and my own work.

No part of this work has previously been submitted for a degree at this or any other university.

References to the work of others have been clearly acknowledged. Quotations from the work of others have been clearly indicated and attributed to them.

In cases where others have contributed to part of this work, such contribution has been clearly acknowledged and distinguished from my own work.

All authors and co-authors of the articles presented in this work report having no conflicts of interest.

Summary

The research conducted in this multi-paradigm investigation aimed to address the question of whether resistance-to-interference (RI) processes are domain-general or domain-specific. Through four comprehensive studies, including a mini-review of behavioral, neuropsychological, and neuroimaging studies (Study 1), normative data collection for stimuli (Study 2), a comparison of RI abilities in young and older adults across domains using carefully matched tasks (Study 3), and an fMRI examination of neural substrates associated with RI (Study 4), the results consistently supported the view that RI is highly specific to the domain. While a general age-related decline was observed in visual, verbal phonological, and verbal semantic domains, the evidence overwhelmingly pointed towards domain-specific RI. This research contributes valuable insights into RI's cognitive mechanisms and emphasizes the importance of considering domain specificity when studying RI. Further investigations with well-matched tasks and robust experimental designs will be essential to advance our understanding of this complex cognitive process.

Foreword

What color is a cloud?
What color is milk?
What color is a simple porcelain plate?
What color is a household appliance?
What color is a candle?
What color is a sheet of paper?
What color is whipped cream?
What color is snow?
— What does a cow drink?

Say "silk" five times. Now, spell "silk."
— What does a cow drink?

The examples mentioned are classic examples of interference. The question "What color is this item?" primes the person to think about color, so they automatically respond with "white" without fully processing the question. The command of saying and spelling “silk” primes certain sounds. When asked, "What does the cow drink?" the earlier priming still influences their response, and they provide an incorrect answer: milk.

This example illustrates how interference can impact our ability to retrieve information accurately and how our responses can be influenced by prior information or context. It also highlights the importance of considering the influence of interference when designing experiments or interpreting results.

As I embarked on my journey to investigate the domain-generality or domain-specificity of interference, I was struck by the pervasiveness of this phenomenon. Interference can impact our ability to perform various cognitive tasks, from perception and attention to memory and language. I remember one time when I was trying to recall a phone number that I had just heard but was distracted by a nearby conversation. Despite my best efforts, I could not keep the interference at bay, and the number slipped from my mind.

This PhD thesis sheds light on this complex phenomenon through a multi-paradigm investigation that includes behavioral and fMRI paradigms and a narrative review paper. By using multiple approaches, the experimental part of this PhD thesis aims to provide a comprehensive understanding of the domain-generality or domain-specificity of interference (in aging). In the final part, this work highlights the challenges of interference and discusses how it can impact our daily lives. It also offers hope by showing how a better understanding of interference can lead to new strategies for managing and overcoming it.

Hopefully, this work offers a better understanding of the brain and how it copes with interference. By identifying the cognitive processes most vulnerable to interference, we can develop interventions and strategies to help (older) adults maintain their cognitive abilities. I also hope this thesis will inspire further research into the fascinating world of interference and inhibitory-like abilities and contribute to our growing understanding of the human mind.

General introduction

Interference is a pervasive phenomenon that affects our ability to perform various cognitive tasks. It can occur in different processes, such as perception, attention, memory, and language, and can significantly impact our daily lives. As we age, interference becomes increasingly problematic, and we may struggle to maintain our cognitive abilities and focus on the relevant elements while ignoring the irrelevant ones.

However, the cognitive neuroscience community has much debated whether Resistance-to-Interference (RI) is domain-general or domain-specific. Some researchers argue that interference is a fundamental cognitive process that operates similarly across all domains. In contrast, others suggest that interference is domain-specific and can vary depending on the cognitive domain or task.

In this PhD thesis, I will present a multi-paradigm investigation into the nature of interference. The introductory section will overview the theoretical foundations defining the research questions. In Chapter 1, we will briefly present some definitions and models and the theoretical framework we will work on. In Chapter 2, we will consider the nature of verbal and visual interference in more detail by providing some well-known examples. In Chapter 3, we will review theories about neurocognitive aging first. Then, we will review current evidence of domain-generality/specificity of interference in normal aging on the one hand and in brain-injured older adults on the other hand.

The experimental part of this thesis will consist of two main sub-parts. The first part will present preliminary works realized before the experiments: a focused mini-review on RI (Study 1) and psycholinguistic norms (Study 2) used in our experiments. Then, Study 3 will assess the domain-generality/specificity question through two paradigms. This study will be conducted in a young, healthy adult population and an elderly healthy adult population. This will allow us to evaluate whether verbal and visual RI tend to have similar or dissimilar trajectories, thus providing insights into our main question. Study 4 will focus on the neural underpinnings of the verbal and visual RI by assessing the same tasks as in Study 3 but in fMRI.

The final part of this PhD thesis will summarize the findings of the different studies and their implications from theoretical, empirical, and societal points of view.

Chapter 1

Resistance-to-interference, a General Overview

The Concept of RI in Cognition

RI corresponds to the capacity to tune out unimportant information so that task performance is not impaired (APA, 2022). It has also been defined as "*the ability to ignore or inhibit irrelevant information while executing a plan*" (p.397) by Dempster and Corkill (1999) and as a subcomponent of inhibition: "*Cognitive inhibition is the suppression of previously activated cognitive contents or processes, the clearing of irrelevant actions or attention from consciousness, and RI from potentially attention-capturing processes or contents.*" (p.142) by Harnischfeger (1995). Therefore, Harnischfeger made a critical distinction between inhibition and RI by proposing that the latter prevents irrelevant information from entering working memory. At the same time, the former involves the active removal of information which are no longer helpful for the current task.

RI was first explored with regard to memory. In the early twentieth century, the **Classical Interference Theory** (McGeoch, 1932) was one of the dominant approaches for studying memory and forgetting (Demonty et al., 2022; McGeoch & Underwood, 1943; Melton & Irwin, 1940). It claims that adults are less likely to remember and recall items if they are associated with a retrieval cue that has also been paired with another item during the maintenance period. New information between the first item's presentation and its recall interferes with its encoding or maintenance (Müller & Pilzecker, 1900), which illustrates reactive interference. After being discussed and updated (Postman, 1961; Postman & Underwood, 1973; Underwood & Ekstrand, 1966), the **Neoclassical Interference Theory** emerged and named what is now Proactive Interference. Proactive interference is the interference at stake before the learning of the task, i.e., prior knowledge and representations, also called 'extraexperimental sources of interference.' Subsequent theories also underlined the competition phenomenon between items' traces: an item may not be obligatorily forgotten but can compete with another interfering item (Anderson & Bjork, 1994). Dempster (1995) recognized a third period of interest for the Interference Theory, labeled as the **Modern Period**, supported by the growing interest in developmental psychology (see Perret, 2003 for a review), neurosciences, neural networks implementations, and increasing research on other cognitive functions such as attention. Since then, the Interference Theories have been disused as they had failed in some cases to prove forgetting in memory in the last century. It also suffered from terminology issues in which ‘(resistance-to)-interference’ and ‘inhibition’ were used interchangeably. In 2000, Nigg updated Harnischfeger's taxonomy and suggested dissociating RI from other inhibitory-related processes. He defined it as a mechanism preventing interference from competition and/or distraction between stimuli and/or resources to maintain a certain level of performance.

From a neuroanatomical point of view, Nigg (2000) suggested that RI originates from a neural network including the anterior cingulate, the dorsolateral prefrontal/premotor cortex, and the basal ganglia. RI has been widely supported by frontal regions and networks (Munakata et al., 2011), especially the inferior frontal gyrus (IFG). In a meta-analysis on 47 tasks requiring RI, Nee et al. (2007) also reported significant bilateral clusters of activations in the dorsolateral prefrontal cortex (DLPFC), inferior frontal cortex (IFC), anterior cingulate cortex (ACC), and posterior parietal cortex (PPC). In another meta-analysis, Hung et al. (2018) showed that the anterior cingulate cortex would instead serve as an information integration center initiating and maintaining the activation of control processes. Moreover, the IFG is structured in three subparts: the pars opercularis, pars triangularis, and pars orbitalis (see Figure 1), which may have different levels of connectivity (Boen et al., 2022). To go further, the left and the right IFG may underpin different cognitive processes (Hampshire et al., 2010; Swick et al., 2008) or may be related to different cognitive domains (e.g., visual, motor, verbal). This potential dissociation will be discussed in *Chapter 2: The Influence of Domain in Cognitive RI*.

Taxonomies and Models

Even though the definition of RI appears straightforward at first sight, multiple approaches and authors tried to classify and detail it in different sub-processes. Various authors have proposed taxonomies based either on conceptual dimensions or/and empirical findings. The main taxonomies are reviewed here in chronological order for clarity.

Dempster (1993) proposed three processes supporting RI. The first process is resistance to perceptual interference. This implies resisting auditory or visual stimuli like sounds or symbols. The second one is resistance to motor interference (motor RI), such as omitting to push on a specific response button that is (no more) relevant. The third is resistance to linguistic interference, inhibiting irrelevant linguistic units such as words or sentences.

Harnischfeger (1995) defined three dimensions of RI: she distinguished behavioral RI (i.e., for motor responses) from cognitive RI (i.e., for mental processes); she also proposed that RI could be either intentional (i.e., controlled) or unintentional (i.e., automatic). Furthermore, she made a critical distinction between inhibition and RI. While the former involves the active removal of information no longer valid for the current task, the latter prevents irrelevant information from entering working memory.

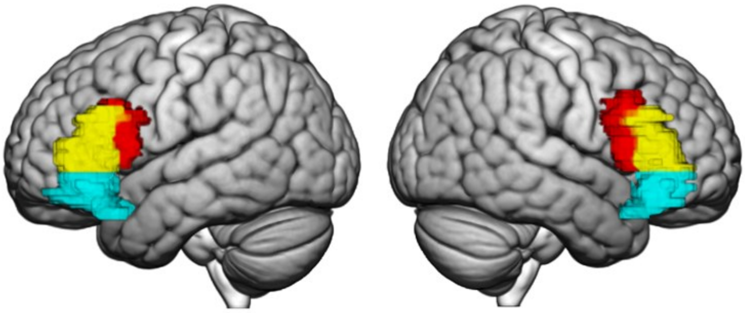
In 2000, Nigg dissociated RI into three main categories. The first one is executive RI, which includes control of interference (i.e., preventing interference from competition between stimuli and/or resources), cognitive RI (i.e., suppressing irrelevant stimuli to protect working memory and/or attention), and behavioral RI (i.e., suppressing prepotent automatic responses) together with oculomotor RI (i.e., unwanted saccades). The second one is motivational RI, which involves the control of responses to novelty and punishment cues. The last one is automatic RI of attention to visual stimuli, such as needed for suppressing recently seen stimuli to suppress unattended locations while attending elsewhere.

Friedman and Miyake (2004) made a similar distinction by identifying three different components. They distinguished distractor interference (i.e., resistance to interference created by irrelevant stimuli while performing a task), prepotent response inhibition (i.e., the ability to suppress dominant, automatic, or prepotent responses deliberately), and proactive interference (i.e., prevent intrusions by stimuli that were previously relevant but are no longer relevant).

Another taxonomy was proposed by Hasher and colleagues (Hasher et al., 2008; Hasher & Zacks, 1988). They classified RI according to its restraining function (i.e., avoiding the production of the most available information before considering other information), deleting function (i.e., decreasing the activation of irrelevant information), or according to its accessing function (i.e., limiting the entry of pertinent information). This classification is also related to the Interference Deficit Theory and will be detailed later in *Chapter 3: the Status of RI in Aging*.

Figure 1

Inferior Frontal Gyri.



Note. The three subparts of the left and right inferior frontal gyri, including the pars opercularis in red, the pars triangularis in yellow, and the pars orbitalis in blue. This figure was built using WFU-generated masks overlaid on a 3D render MRI template using MRICroGL (http://www.nitrc.org).

A Close-up of Terminologies

Authors use different terms to name RI in their works based on the previous taxonomies. For simplicity, widely used terms in scientific articles are defined here regarding theoretical processes and empirically targeted cognitive domains.

Processes. RI (or inhibitory-like processes) is sometimes referred to as being controlled versus automatic or intentional versus non-intentional. Both terminologies are pretty close to each other. The first approach was defined by Nigg (2000), whereas the second is based on Harnischfeger's (1995) conceptual framework. ***Controlled inhibition*** is limited to the conscious, deliberate, and controlled suppression of unrelated inputs or reactions and automatic inhibition. ***Automatic inhibition*** refers to inhibitory processes taking place without awareness. ***Intentional inhibition*** refers to the deliberative implementation of the mechanism handling irrelevant external or internal input. ***Non-intentional inhibition*** is considered without access to conscience and functions as a filter to choose the information that would become accessible to the conscience. Another pair of terms is often encountered in the literature: proactive and reactive inhibition/cognitive control (Braver, 2012; Braver et al., 2021). ***Proactive cognitive control*** is the act of maintaining goal-relevant knowledge in working memory to support an adaptive response to an impending event. ***Reactive cognitive control*** is used as a late correction mechanism that is only activated when necessary, in a just-in-time manner, such as following the detection of a high interference event (Stuphorn & Emeric, 2012).

Domains. A few authors have distinguished RI concerning different cognitive domains (i.e., a specific area or aspect of cognitive abilities and processes such as visual and verbal processing). Dempster and colleagues (Dempster, 1993; Dempster & Brainerd, 1995; Dempster & Corkill, 1999) were the first to propose a taxonomy according to perceptive, motor, and linguistic domains. Jennings et al. (2011), Nassauer and Halperin (2003), Germain and Collette (2008), and Stawarczyk et al. (2012) also supported a dissociation between motor and perceptive RI. In these studies, perceptive RI was assessed with a Stroop, a perceptual Simon task, and a Flanker task; motor RI could be assessed with a motor Simon task, a saccadic task, a Go/No-go task, and a Stop-Signal task; and both via the Motor and Perceptual RI Test. Studies on linguistic RI are mostly referred to as broader executive processes in language processing (e.g., Peristeri et al., 2011). This topic will be detailed further in *Chapter 2: The Influence of Domain in Cognitive RI*.

RI & Working Memory

RI is inherently related to other cognitive functions. D. M. Burke & Osborne (2007) defined it as a process that controls working memory and attention, affecting general cognitive performance, including the capacity to focus, understand and use language, solve problems, and learn new information. To perform cognitive tasks like processing or reasoning, the ability to temporarily store information, with or without additional manipulation, is called working memory (WM). In the last years, RI (and inhibitory-like abilities) has been studied in the context of WM(Carlson et al., 2002; Rey-Mermet et al., 2019, 2020; Szmalec et al., 2011; Unsworth et al., 2020). To be sufficiently efficient, the memory system has to perform several tasks. First, it must determine if the information is relevant enough to enter WM. Next, it must transfer this information to the appropriate network and resist irrelevant information from entering WM. Finally, it needs to update information in WM and retrieve information from long-term memory to WM while resisting irrelevant competitors or external elements. In these different stages, distraction and interference can occur (see Lustig et al., 2007 and Campbell et al., 2020, for a recent presentation). Following these steps, Hasher and Zacks described three RI functions operating simultaneously during information processing: access, deletion, and restriction. The interplay between RI and WM being unavoidable, the theoretical model considered in this thesis is described below.

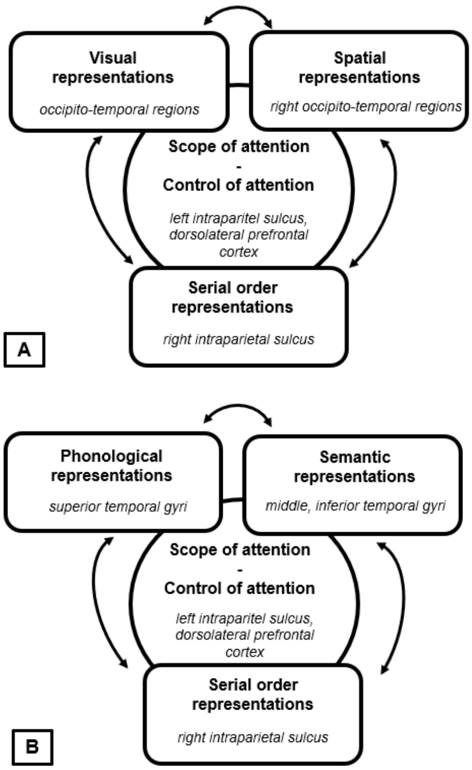
Multi-component theories assume that items from different sensory domains (visual and verbal) are stored and maintained through different mechanisms (Baddeley & Hitch, 1974; Cocchini et al., 2002; Ruchkin et al., 2003). The model proposed by Baddeley (1983, 2000, 2003, 2010) had already predicted the existence of two separate domain-specific sub-systems: one verbal and one visuospatial. Even though models of WM have evolved for many years, different and separate components were predicted when it comes to the verbal and the visual domains; thus, separating RI within a verbal system on one side and a visual system on the other side (Majerus, 2014a, 2018a). This model suggests that the same neuroanatomical area (the dorsolateral prefrontal cortex) underpins both mechanisms, presupposing a domain-general functional brain activity. Evidence in favor of domain-specific RI mechanisms arises from studies showing that interference occurs when two concurrent tasks have same-domain material, either verbal or visual, but not (or very little) when the material differs (Camos, 2017; Meiser & Klauer, 1999; Salway & Logie, 1995; Shah & Miyake, 1996)

In contrast, the domain-general view assumes that items from different sensory domains (visual and verbal) are stored, maintained, and retrieved by a unique system (Cowan et al., 2011; D. Li et al., 2014). The domain-general view also predicts that common brain regions underpin both mechanisms. Interestingly, Li et al. (2014) showed that **both views are not incompatible**. Their analysis revealed that visual and verbal WM showed common brain activity during encoding, maintenance, and retrieval. In contrast, some domain-specific networks were more activated when the WM load varied during encoding, confirming a previous behavioral study by Saults and Cowan (2007). Jarrold et al. (2011) also suggested that domain-general and domain-specific effects should be considered when studying a cognitive mechanism such as WM.

The present PhD thesis is framed by the Attention-Order-Short-Term-Memory or A-O-STM model (Majerus, 2013, 2014a, 2018b), a recent integrative model. The A-O-STM model makes explicit three processes involved in short-term tasks in relation to the brain structures underlying them. This model suggests a verbal and visual WM framework (see Figure 2). Verbal WM is described as a temporary activation of the language system, underpinned by the temporal gyri, a serial order processing underpinned by the right intraparietal sulcus, and selective attention, underpinned by the left intraparietal sulcus. Visual WM is also described with attentional and serial order components underpinned by the same regions. Still, it is also described in relation to visual representations underpinned by occipitotemporal regions and spatial representations underpinned by the right occipitotemporal regions.

Figure 2

Visual (A) and Verbal (B) A-O-STM Models Based on Temporary Activation of the Language System, Serial Order Processing and Selective Attention (Majerus, 2013, 2014, 2018a).



Chapter Summary

This chapter introduced the reader to RI as the ability to resist automatic and interfering behaviors, acting like a filter supported by the frontal cortex. Several taxonomies and terminologies are used in the literature to encompass RI. In this thesis, we will focus on cognitive RI, the cognitive process responsible for restraining and deleting irrelevant language or visual-related action/thought to achieve a specific goal and allowing a good functioning of WM (and, thus, the other cognitive functions). The following chapter will present empirical works about visual and verbal RI.

Chapter 2

The Influence of Domain in Cognitive RI

Verbal RI in Behavioral and Neuroanatomical Studies

Cognitive RI within the linguistic system allows us to remove language representations that are no longer pertinent to achieve a specific task and, therefore, to resist verbal interference. Two types of verbal RI can be described: semantic RI makes it possible to decrease irrelevant semantic activations, while phonological RI decreases irrelevant phonological activations. Typically, verbal errors arise as language intrusion, such as saying a wrong word semantically (e.g., cap) or phonologically (e.g., bat) related instead of the right one (e.g., hat). Most known verbal cognitive RI tasks will be presented with specific attention to semantic and phonological RI paradigms, followed by neuroanatomical and functional studies.

One way to assess cognitive RI is the well-known **Stroop task** (Stroop, 1935), in which participants are asked to verbalize the font color of written color words aloud. Classically, a comparison is made between an incongruent and a congruent condition. In the congruent condition, font color and written color words are similar (e.g., the written color word "GREEN" in green font). Conversely, the font color and written color words are different in the incongruent condition (e.g., the written color word 'BLUE' in green font). Slower verbalization latencies are generally observed in the incongruent condition compared to the congruent condition. Most contemporary literature converges to interpret the Stroop effect as a decrease in cognitive RI. The Stroop effect is indifferently observed in young or older adults (West & Alain, 2000) and even in people with a verbal deficit, such as aphasic patients (Pompon et al., 2015). It should be noted that some studies emphasize within and between subject variability (Kalanthroff et al., 2018; Melara & Algom, 2003), mirroring a more complex mechanism.

Another classic task that comes to mind when working on cognitive RI: the Go/No-Go task. In a classic **verbal Go/No-go paradigm**, participants must respond as quickly as possible (Go) to a certain class of stimuli (words or sounds) by pressing a keyboard key and not responding to other classes of stimuli (No Go). Presenting more Go trials than No-Go trials creates a prepotent response, and participants must inhibit an inappropriate response (Georgiou & Essau, 2011). This phenomenon echoes the errors of commission, which reflect an RI deficit for the No-Go stimulus. Omission errors correspond to an absence of the response for the Go stimulus. Commission errors, omission errors, and response times are calculated and allow to highlight more commission errors and slower response times for No-Go trials.

Semantic Modality

In the 80s, Tipper was one of the first authors to examine inhibitory mechanisms more deeply (Tipper, 1985, 2001; Tipper & Cranston, 1985; Tipper & Driver, 1988). In 1985, he first described the level of internal representation aroused by to-be-ignored stimuli, thus implying RI processes. The internal representation of ignored drawings might be associated with RI during selection. It also suggests that prior exposure to a stimulus, even if it does not require specific attention, unfavorably influenced the response to this stimulus. Such an effect has been called the **Negative-Priming (NP) Effect**. Then, in 1988, Tipper and Driver wondered to what extent to-be-ignored stimuli were processed. They examined the level of representation aroused by words or pictured words visually presented and randomized their presentation between different categories. Their data suggested that subsequently ignored words or pictured words achieve categorical processing. Therefore, even though stimuli are visually presented, they do reach a semantic treatment. Tipper eventually contributed to show that visual inhibitory mechanisms could imply verbal semantic processes. Later on, Frings et al. (2015) concluded that given the complex structure of the NP paradigm, one could argue that it is not a pure measure of RI. Hence, it implies both RI and/or retrieval mechanisms, depending on the reached cognitive level (i.e., perceptual, visual, categorical …). These assumptions meet one main limit from the visual paradigms generally used to measure cognitive RI: long-term verbal memory has too many implications, such as semantic categorization. Even more recently, Archambeau et al. (2020) examined proactive interference caused by one negative-priming paradigm derivative: recent-negative paradigms (Monsell, 1978) through a diffusion decision model (DDM, see Ratcliff et al., 2016 for a review). When reanalyzing studies proving an age-related sensitivity to proactive interference with DDM, authors showed that inhibitory processes observed with this paradigm remain intact in older adults.

The Hayling Sentence Completion Test (Burgess & Shallice, 1997) is a second well-known paradigm. It measures RI via its response initiation (i.e., automatic response) and response suppression (i.e., response to inhibit). It includes two sets of fifteen sentences, of which the last word is missing. In the first set, the initiation or automatic condition, the participant must complete the sentence with a word associated with it (e.g., "He posted the letter without putting a stamp"). In the second set, called the RI condition, the participant must complete the sentences with a nonsense ending word and thus inhibit the pertinent one (e.g., "To see better up close, he must wear pineapples"), giving a measure of response suppression ability within the verbal domain. As written by Cervera-Crespo & González-Alvarez, (2017), the Hayling test is mostly used to assess semantic failures. It has been proven in different populations, such as older adults, who tend to show increased latencies in the RI condition, meaning that with aging, adults tend to have more difficulties inhibiting semantic information.

Several paradigms (see in Roelofs, 2018) experimentally manipulate semantic interference via blocked pictures paradigms such as picture-word interference tasks, alternating picture naming and naming to description, speeded picture naming, and the **semantic blocked naming tasks** (Belke et al., 2005; Biegler et al., 2008; T. Schnur et al., 2006). As Belke et al. (2005) describe it, participants have to repeatedly name sets of objects with semantically related names (e.g., cat, dog, fish = homogeneous sets) or unrelated sets (e.g., chair, cat, broom = heterogeneous sets) in the semantic blocking paradigm. Participants often perform slower and with increased error rates and slower naming latencies when the set is from the same semantic category. Such a result reveals a more effortful naming process compared to heterogeneous sets. Rather than a deficit in the postelection RI process, it shows that the effect is due to semantic interferences of the previously named items competing activation. These results constitute further evidence for within-category interference effects in which semantic cognitive RI mechanisms are deficient.

Phonological Modality

Alongside the involvement of RI in the semantic modality, recent works have also showed the importance of RI and control skills when performing phonological tasks. Feng & Qu (2020) investigated the contribution of phonological relatedness on written production using the blocked cyclic naming paradigm described above. By showing interference effects in both reaction times and error rates, the authors found that phonological syllabic overlap between stimuli could lead to phonological interference. Notably, these results are inconsistent compared to the previous studies reporting a facilitation effect (Meyer, 1990, 1991). This difference in findings could be discussed regarding the model proposed by Chen & Mirman (2012), according to which "*core computational principle that determines whether neighbor effects will be facilitative or inhibitory: strongly active neighbors exert a net inhibitory effect and weakly active neighbors exert a net facilitative effect*" (p.10). The aspect that perhaps most justifies the existence of a phonological RI process is the cognitive treatment of phonological priming - two phonologically overlapping words are presented, and the first word influences the accuracy and the speed of answering to the second word (Slowiaczek & Hamburger, 1992). An increasing number of errors and longer latencies can also be found, but mostly when the prime active strongly active phonological neighbors (Dufour & Nguyen, 2017; Ouyang et al., 2020; H. Yang et al., 2021).

Neuroanatomical studies

For a long time, neuroimaging studies have claimed that the left frontal region, including the Broca area, was a seat for language, being activated during various language tasks and this, even when it did not involve overtly a production of speech (Gabrieli et al., 1998). Broca's area is thus defined by its major implication in many language functions, such as active language retrieval, linguistic and non-linguistic representations, and conflict resolution of competing lexical representations during verbal production (Schnur et al., 2009). If different regions house different representations, the nature of RI would also be split according to the phonological modality on the one hand and the semantic modality on the other hand, thus rejecting the hypothesis of a concept of RI with general cerebral correlates (R. C. Martin & Lesch, 1996). This aligns with some language models in which the neuroanatomical networks underlying language processing would be divided according to whether we are dealing with semantic or phonological information (Majerus, 2013). Poldrack et al. (1999) identified the inferior prefrontal cortex (IFC) as the cerebral seat for cognitive RI. More precisely, the dorsal IFC would be more activated for semantic decisions whereas the ventral IFC would be more activated for phonological decisions. This is also consistent with the cortical organization of lexical knowledge suggested by Gow (2012), in which language production and comprehension networks are underpinned by two neuronal pathways: dorsal and ventral. The dorsal pathway in the inferior parietal region would house the phonological representations. In contrast, the ventral approach in the posterior superior temporal sulcus and middle temporal gyrus would serve as an interface for semantic representations. Fiez (1997) highlights another dissociation of the left PFC, this time between its anterior and posterior part according to the different modalities (phonological vs. semantic) of the information to be processed. The anterior part of the left PFC would be more active during a semantic decision task, while the posterior part would be more active during a phonological task. In her literature review, Julie Fiez underlined the involvement of the inferior prefrontal cortex but attempts to localize precisely the different underlying neural mechanisms were few. We can now underline different methodological biases and cognitive cofounds. For example, Petersen et al. (1988) used lexical and semantic material in the different tasks; thus, concluding on separate underlying neuronal networks seems limited.

In contrast, Gold et al. (2005) suggested that the left anterior inferior prefrontal cortex and the posterior left inferior prefrontal cortex would both be involved in the language control process. Nonetheless, authors still argue for a domain-specificity of the left posterior frontal and temporal regions, but the cognitive-related process is unclear. Paulesu et al. (1997) also noted activation in both anterior triangular left IFG and left thalamus for phonological and semantic tasks, but greater activation in the posterior opercular left IFG and a greater left retrosplenial activation for phonemic fluency and semantic fluency, respectively. These data again show consistent results in the literature arguing for specific activation of the left lower prefrontal cortex according to verbal sub-modalities. Furthermore, when focusing on fMRI investigations of the well-known Stroop, a stronger activation into the cingular cortex is observed (Gruber et al., 2002; Peterson et al., 1999). Again, activated regions differ depending on the Stroop version used (Song & Hakoda, 2015): regions in a Stroop and reversed Stroop are inconsistent. In another Stroop study, aging people showed a decreased activation in the anterior cingulate cortex, dorsolateral prefrontal and parietal cortices, and increased activation in ventral visual regions (temporal regions) and anterior inferior prefrontal cortices. The authors suggest that the three first cited regions are normally involved in the form of control, and older adults are trying to recruit visual regions to compensate for a frontal deficit.

Many studies investigated the neural basis of verbal processes, but only a few investigated verbal cognitive RI. Most studies are focused either on both language and linguistics features on verbal working memory mechanism rather than RI.

Visual RI in Behavioral and Neuroanatomical Studies

Visual cognitive RI is responding correctly to a visual target or stimuli while ignoring the irrelevant visual context. It can manifest while driving when you have to focus on the red traffic lights while the pedestrian light is green. Both stimuli are important in this situation, but you should inhibit the green color of the pedestrian light and stop your drive. This section will review visual cognitive RI and present the main paradigms used (i.e., Go/No-Go task, Flanker task, and eye-tracking), their main effects, and the related neuroanatomical studies.

In the early seventies, Eriksen & Eriksen (1974) aimed to measure the suppressing response ability depending on the visual context (i.e., the flankers). For that purpose, they designed the **Eriksen flanker task** composed of a target stimulus flanked by irrelevant stimuli, which are either oriented in the same direction (i.e., congruent flankers) or either the opposite direction (i.e., incongruent flankers) or to neither (i.e., neutral flankers). In their original experiment, Ericksen & Ericksen used letter stimuli: participants had to press a lever to the right if 'H' or 'K' flanked the fixation point or to the right if an 'S' or 'C' flanked the fixation point. Here, the congruent flanker context could be "KKKHKKK"; the incongruent flanker context could be "SSSKSSS" and the neutral one "JGKSJGK." Accuracy and reaction times are recorded and compared between congruent and incongruent trials to evaluate to what extent participants inhibit the contextual incongruent stimuli. Two different effects can be underlined: a facilitating effect attributed to the repetition between flanker and target information and an interfering effect explained by the overlap between flanker-driven and target-driven responses. Since then, the Flanker task has developed many variants (color, shape, arrows) to study visual distractibility and cognitive RI. For instance, Kopp et al. (1994) manipulated arrows pointing in the same direction as the target for the congruent condition (i.e., <<<<< or >>>>>) or in the opposite condition for the incongruent condition (i.e.,<<><< or >><>>). Rafal et al. (1996) manipulated a colored flanker similar to the target for the congruent condition (i.e., ■■ or ■■) whereas a dissimilar flanker color was used in the incongruent condition (i.e., ■■ or ■■). In the same vein, Lindgren et al. (1996) adapted the task with numbers similar to the target for the congruent condition (i.e., 22222 or 33333) and different for the incongruent condition (i.e., 22322 or 33233). Subjects were asked to press a key response to the central target accordingly to the instructions. Overall, results show that participants respond more slowly in the incongruent condition than in the congruent condition. This difference is the Flanker Effect and is still observable in the last studies (Erb et al., 2020; Haciahmet et al., 2021).

While Flanker's work was developing, the Go/No-Go paradigm was not left behind regarding visual cognitive RI. Indeed, the visual Go/No-Go evaluates visual response RI (Donders, 1969) and tests the capacity not to respond to a visual stimulus, called the No-Go condition, and respond to other stimuli, called the Go condition. In general, the Go stimuli are presented more often than the No-Go stimuli, resulting in a tendency for the subjects to answer. Thus, the response tendency must be inhibited if the No-Go stimuli are presented. For instance, in the Test Battery of Attentional Performance (Zimmerman & Fimm, 2002), two symbols (i.e., ✕ and ✚) are randomly presented on the screen. Participants have to press a key as quickly as possible when they see the ✕ symbol, the Go condition, and not when they see the ✚ symbol, the No-Go condition. As for the Flanker task, there are many incorrect responses and reaction times that are significantly slower than those obtained in the simple detection tasks. Comparatively to the Flanker task, different variations exist: with colored squares (e.g., ■ Go or ■ No-Go in Wessel, 2018), equiprobable Go/No-Go trials, longer interstimulus intervals, or parametric Go/No-Go (Weidacker et al., 2017). As the decades go on, the visual Go/No-Go paradigm is still in use to measure visual discrimination and visual cognitive RI, especially from developmental (E. Y. Kim et al., 2007), neuropsychological (Ettinger et al., 2018), and neuroanatomical points of view.

Even though we have decided not to focus on motor and oculomotor RI, we will shortly review eye-tracking measures regarding cognitive RI functioning. Indeed, a whole bunch of the literature tends to explain how oculomotor movements and activity reflect different cognitive processes (Noiret, 2017). In his PhD thesis, Noiret (2017) described oculomotor saccade characteristics relative to working memory and executive functioning, especially RI (Leigh & Kennard, 2004), and this is based on research on human cognitive control abilities. The main data come from antisaccade and prosaccade measures. In these tasks, volunteers have to fixate visually on a central stimulus. A sudden onset target that appears to its left or its right then replaces this stimulus. Participants are asked not to focus on the peripheral stimulus but to direct their gaze in the opposite direction. Most of the time, participants failed to do it correctly and made reflexive glances toward the target, called a prosaccade. Only a few eye-tracking studies brought additional information on visual cognitive RI with healthy patients, as it is commonly used in patient populations. Most studies on healthy patients focused on age-related visual cognitive RI measures. Some authors showed that age-related inhibitory functions are relatively intact and indicated that inhibitory oculomotor functions decreased only when older adults' working-memory capacity is overloaded (Eenshuistra et al., 2004). Conversely, Noiret et al. (2017) suggested that age-related cognitive decline and saccadic eye movement could be associated with decreased processing speed and executive attention in prosaccade and antisaccade tasks. Older adults take more time to decide when goal maintenance and RI are involved in the task. Taken together, these data suggest, on the one hand, that decline in aging can be observed when focusing on control and RI functions (Braver & West, 2008; Juhel, 2003; West, 1996; Zanto & Gazzaley, 2014). On the other hand, these visual RI paradigms often share common processes with attention and verbal concepts, as we will discuss below.

Despite many empirical studies supporting verbal cognitive RI, the processes supporting visual cognitive RI remain poorly understood. According to the few studies exploring visual RI, the frontoparietal network is considered the main network underlying visual search, orientation in space, and goal selection (Corbetta, 1998). Considering Corbetta's review, which is focused on the relation between spatial attentional processes during covert orienting on the one hand; and on attentional processes linked to oculomotor processes on the other hand, we wonder to what extent the frontoparietal network could also underlie the visual inhibitory process. Growing evidence supports this assumption. First, Chadick et al. (2014) examined the role of the medial PFC in the distractibility and suppression processes and their decline in aging by using a visual experimental paradigm where participants had to inhibit distracting stimuli to complete the task successfully. The authors evaluated the neural basis of distraction's impact on WM tasks before comparing this neural basis to older adults' neural basis in response to distraction. Results showed an alteration of the medial PFC connectivity. In addition, the authors showed an association between the magnitude of the WM distractibility, the neural suppression, and the differences in cortical volume and activity of the medial PFC in the older group. Second, by using a 1-back task with faces, objects, body, and scenes stimuli, Weeks et al. (2020) showed that the medial temporal lobe is related to "the importance of long-term memory" retrieval mechanisms in the context of high-load working memory tasks that place great demands on attentional selection mechanisms." Furthermore, the authors pinpoint this area as being involved in regulating and retrieving information in WM – what we can relate to the suppression function of RI.

To go back to our different tasks, Wager et al. (2005) identified bilateral anterior insula/frontal operculum and anterior prefrontal, right dorsolateral and premotor, and parietal cortices as common regions activated during a Flanker task, a Go/No-Go task, and a stimulus–response compatibility task. The right dorsolateral gyrus was the only isolated region per se compared to the other regions activated in both hemispheres. This is in line with McNab et al. (2008), who studied working memory and cognitive RI in an fMRI protocol. When isolating the inhibitory mechanisms in three tasks (Go/No-Go, Flanker, and a stop task), they discovered that the right inferior frontal gyrus may be more specific to the cognitive RI involved. In contrast, parietal regions may be more specific to the WM storage process. In Zhu et al. (2010), participants performed a Flanker task. Young adults activated more of their medial frontal gyri and precentral gyri, whereas they only unactivated the right inferior frontal gyrus. This again indicates a certain type of hemispheric specialization for cognitive RI for visual stimuli.

Interestingly, Simmonds et al. (2008) have summarized some Go/Go-No studies in a meta-analysis. They showed that a dominant right lateralized network seems more implicated in cognitive RI in Go/No-Go tasks. Regions such as the rostral superior medial wall, right middle/inferior frontal gyrus, bilateral inferior parietal regions, occipital regions, putamen, and left premotor cortex are more activated to suppress irrelevant visual stimuli. The authors underlined that the rostral superior medial wall (i.e., pre-supplementary motor area, pre-SMA) activation may be due to the RI of motor actions when performing the tasks as it overlaps with the response selection mechanism (Obeso et al., 2013; Schaum et al., 2021). This is also in line with Michael et al. (2006) results showing an implication of the right frontal operculum into the motor response selection/RI more than in the visual cognitive process involved in the task (A. R. Aron et al., 2003, 2004). As for the dorsolateral regions (i.e., middle frontal gyrus, MFG), their activations may be due to working memory load, depending on the tasks' difficulty: the more difficult the task, the more this region is recruited. The role of parietal regions would be to help maintain representations and stimulus-response associations. In other words, it links the participants' decision when seeing/processing a stimulus and the motor response.

Nonetheless, one may say that these results cannot be completely attributed to visual networks and visual RI mechanisms as they implied some language-related processes. Indeed, in Chadick et al. (2014) and Weeks et al. (2020), faces and scenes were used as stimuli implying long-term representations to encode and recall them correctly. One possible solution could be creating visual material that does not imply language representations. Moreover, precautions have to be taken when considering the right IFG: its implication has often been found in motor RI (i.e., with stop-signal tasks) and may be related to the RI of a predominant motor response (Hampshire et al., 2010; Lenartowicz et al., 2011; Schaum et al., 2021).

How to Dissociate the Different Domains in RI?

Even though we have just described several ways of measuring verbal and visual cognitive RI, only a few studies are investigating both with comparative methods. Palladino et al. (2003) compared visuospatial and verbal cognitive RI performances. To achieve this, they designed the tasks with identical structure, conditions, and the number of items to remember. Participants had to replace previously memorized targets on a matrix for the visuospatial task. The number of items to be recalled varied by asking participants to replace four, six, or eight items on the matrix. Matrices were composed of words for the verbal task, built on the same principle. Participants had to recall four, six, or eight words regardless of their position in the matrix. Interference was introduced into the two tasks through an RI condition in which green or red-colored distractor items were added during the encoding or storage phase of the matrices. Participants only had to recall items presented in a certain color and therefore disregard the others to answer correctly. In this study, the authors measured the percentage of intrusion errors (i.e., distracting items wrongly recalled). They noted that the more elements there were to inhibit, the more likely intrusion errors occurred, but only in the visual domain. In the verbal domain, they observed the reverse profile, which suggests the existence of different RI processes depending on the cognitive domains.

Only a small part of the paradigms described above have been used for systematic comparisons between different cognitive domains, notably the Go/No-Go task. In 2016, Nakata et al. investigated visual and verbal/auditory cognitive RI by designing a visual Go/No-Go and an auditory Go/No-Go. The visual Go/No-Go stimuli were red and green circles with the equiprobability of random appearance. The auditory stimuli were 2,000 Hz and 1,000 Hz sounds. Behavioral data showed more omission errors in the auditory than the visual condition, indicating a greater difficulty in responding in the auditory modality.

Another task that is also prone to cross-modalities design is the Flanker task. For instance, Schumacher et al. (2011) evaluated visual and verbal/auditory cognitive RI by eliciting interference via two Flanker tasks identically built. Behavioral results confirmed the congruency effect of Eriksen & Eriksen in 1974, but participants were generally slower to perform the task in the auditory condition. Notably, they used the same material (e.g., letters) but in two different presentation modalities. Thus the material itself was not that different. These behavioral data seem consistent with a domain-specificity cognitive RI mechanism.

Lastly, even though the Stroop test is known as a gold standard for evaluating cognitive RI, it is mostly cross-modality designed rather than between-modality designed. For example, Donohue et al. (2013) examined, among other variables, to what extent participants could focus on one modality over another while performing a bi-modality Stroop. To be clearer, participants attended to a target auditory word (e.g.," blue") preceded by an irrelevant written stimulus (e.g., "red"). For half of the session, they had to focus on visual modality and report the identity of the visual word while ignoring the auditory word. For the other half, they had to focus on auditory modality and report the identity of the auditory word while ignoring the visual word. Participants were more penalized when they attended the auditory modality and were distracted by visual stimuli than when they attended the visual modality with auditory distractors. Several data sets aim to study the Stroop test as a cross-modal design (Cowan & Barron, 1987; E. M. Elliott et al., 2014; Roelofs, 2005), other studies evaluated the response modality (e.g., oral or manual; Ikeda et al., 2010; Redding & Gerjets, 1977) but almost none of them aim to compare two different modalities with different materials like verbal versus non-verbal material.

After independently examining the verbal and visual inhibitory neural networks, we will summarize works comparing both mechanisms. Stephan et al. (2003) addressed this comparison through a letter decision task and a visuospatial decision task. They concluded that inhibitory processes seem localized in the anterior cingular cortex and frontal gyrus, respectively, in the right hemisphere for the visual process and the left hemisphere for the verbal process. Other authors, such as Leung & Zhang (2004), support this hypothesis of the non-unitary nature of the inhibitory process according to modalities. Still, they only studied an interference resolution process in a spatial working memory task. Thus, their measures are not comparing verbal and visual cognitive RI. However, a general conclusion can be drawn: the implication of the inferior frontal gyrus into cognitive RI, whether we consider its verbal or visual aspect.

Although some behavioral studies examined the paradigms with different modalities by strictly comparing them (verbal vs. visual) or within cross-modal designs, neuroimaging studies have conducted lesser investigations on that topic. One of the few studies found is focused on a modified version of the Flanker task. Indeed, Morimoto et al. (2008) explored hemispheric specialization in the prefrontal cortex in regard to the verbal or nonverbal modality of the Flanker task. Two different versions of the flanker were used: a color word flanked by a colored patch or a colored patch flanked by a color word. Results showed that the left IFC was more activated when a word had to be inhibited, whereas the right IFC was more activated when a colored patch had to be inhibited from performing correctly. This study supports a neuroanatomical domain-specific view of cognitive RI.

To sum up, we reviewed behavioral evidence for verbal RI on the one hand, either directly via phonological and semantic modality or more general verbal paradigms. On the other hand, we reviewed visual RI through Go/No-Go, Flanker, and eye-tracking tasks. Several studies highlight performance differences between verbal and visual domains, thus suggesting a more domain-specificity of cognitive RI. Nonetheless, this evidence suggests that the different performances could also be task-dependent as almost no literature compares two inhibitory domains. Studies examining dissociations between verbal and visual inhibitory networks highlight heterogeneous results showing a tendency to dissociate between the right and the left IFG. However, the diverse nature of the equipment used in these tasks may explain these inconsistencies. Indeed, some tasks refer to verbal material, but this is presented visually. It, therefore, appears important to bring clarifications to these studies examining the effects of the cognitive domain because verbal information can be presented auditory or visually or both, which implies transmodal processing. Likewise, visual information can relate to the verbal and non-verbal domains.

Chapter Summary

This chapter reviewed behavioral and neuroimaging works on verbal and visual cognition RI. Conversely, verbal RI is probably more studied with well-known paradigms such as the Stroop, the Hayling test, the verbal Go/No-Go, the Negative-Priming, or the Blocked-Cyclic Naming tasks. On the other hand, visual RI is less studied when it comes to elaborated cognitive RI, not only visual-motor parameters. It is mostly evaluated with classic Go/No-Go, Flanker tasks, and eye-tracking measures. For visual and verbal domains, worse performances (precision and/or response time) are observed in the interference condition, requiring RI to avoid/delete irrelevant information to achieve a specific task. When considering neuroimaging data, verbal RI would preferentially be supported by the left PFC, whereas the right PFC would preferentially support visual RI. However, almost no studies compared both domains with the same design, either behaviorally or neurofunctionally, and more specific works need to be done on this topic. One way to do so could be to compare both domains in advanced age: are both domains undergoing the same cognitive and neuroanatomical changes, or are they undergoing different changes? In the next chapter, we will review the main theories of aging, the specific involvement of cognitive RI, and, more directly, how verbal and visual inhibitory domains are processed with advanced age.

Chapter 3

What is the Status of RI in Aging?

Main Models of Neurocognitive Aging

In 2021, Murphy et al. defined neurocognitive aging as "*[...] the physiological and behavioral changes that occur in the brain that are associated with increases in chronological age*" p.3466. Several hypotheses have attempted to explain the effects of age in physiology and behavior independently of any disease, also called healthy aging. On the one hand, several hypotheses underlined age-associated disorders on a behavioral level. Behavioral age-related manifestations are accompanied by cognitive functions decline, such as attentional resources (Craik & Byrd, 1982), processing speed (Salthouse, 1996a), executive functions (West, 1996), working memory (Baddeley, 1996), and RI/inhibition (Hasher & Zacks, 1988) (for a review, see Angel & Isingrini, 2015). On the other hand, physiological changes occur simultaneously in the brain with advanced age. Key findings are numerous on white/grey brain volume and integrity loss (Raz et al., 1997; Raz & Rodrigue, 2006), vascular changes (Goldstein et al., 2005), changes in brain activity (Cabeza et al., 2002), modification in cellular communication (S. N. Burke & Barnes, 2006) and senescence (Sikora et al., 2011) and different levels of inflammation and neurotoxins (Bennett et al., 2012). In this section, we will briefly present biological changes coming with advanced ages, the main cognitive theories of aging, and the main age-related neurocognitive theories. Finally, we will detail the Interference Deficit Theory and visual and verbal age-related inhibitory literature.

Biological Changes with Advanced Age

To define neurocognitive aging conveniently, it is essential to specify physiological changes occurring in the brain and their consequences for cognition (see Figure 3) - the interdependence between both being rather obvious.

Some age-related changes regarding gene expression have also been mentioned at the genetics level (Sibille, 2013). Genome-wide-based studies have shown some changes in gene expression associated with aging. However, it is noteworthy that the number of concerned genes remains small (around 5%) but is also quite variable from one study to another. This variation is mainly due to the inclusion of both normal healthy aging participants and pathological aging participants. Gene expression changes include genes coding for neuropeptides, trophic factors, receptors, and other disease-associated genes.

At a **molecular level**, inflammation and neurotoxicity occur with aging, mainly caused by oxidative stress. The mitochondrial free radical theory postulates that aging is due to the accumulation of oxidative damage to lipids, DNA, and proteins. Proteins accumulate and can be toxic, as for β-amyloid in Alzheimer disease and α-synuclein in Parkinson disease. When it comes to mitochondria, their functions are dysregulated by abnormal gene expression at the genetic level. These dysregulations are also responsible for DNA damage repair dysfunction (Yankner et al., 2008), such as telomere shortening (Shammas, 2011). Finally, molecular aging is also associated with modifications in the metallic ions levels (iron, manganese, zinc, and copper), which are involved in healthy and neurodegenerative aging (Haase & Rink, 2009; Takeda, 2003; Ward et al., 2014).

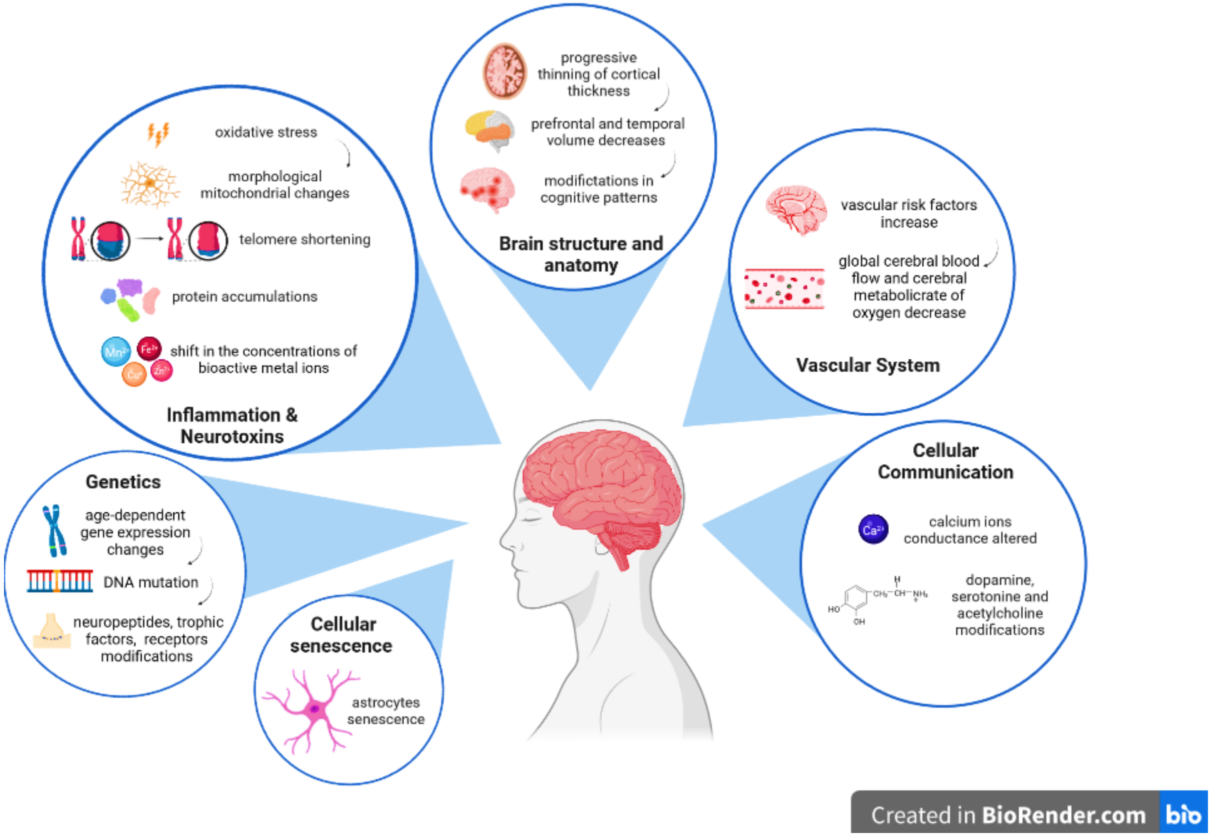
Moreover, neurotransmitters such as dopamine are also involved in age-related processes. First, proposed a **dopaminergic neuromodulation theory** of age-related deficit (S.-C. Li et al., 2001; S.-C. Li & Rieckmann, 2014; S.-C. Li & Sikström, 2002). Due to a loss of some dopaminergic receptors in aging, mainly D2 and D1, dopamine (DA) cannot be as fully integrated as in adulthood. Some studies further showed that this decreased available dopamine leads to less distinctive activation patterns. Dopamine has also been related to Dual-Mechanism control, which we will describe in more detail below. In sum, this model describes proactive and reactive control that differ in terms of the dopaminergic system. While D1 receptors are involved in information maintenance, D2 receptors are associated with cognitive flexibility and task-shifting. The balance between D1 and D2 receptors is regulated by DA concentrations, with D2 receptors being more responsive to lower levels of DA and D1 receptors preferentially responding to higher levels. Understanding this interplay provides insights into how DA modulates cognition in aging. For a complete discussion, one may refer to Matzel and Sauce (2023).

At the **cellular level**, changes in cellular senescence also occur with aging (Sikora et al., 2011). There is a decrease in the density of dopaminergic neurons and transmitters in serotonin and acetylcholine receptors, a reduced synaptic density, and an altered calcium ions (Ca^{2+}) conductance. These cellular changes play a major role in brain communication and networks, meaning the transfer of information. For example, dopaminergic receptors become scarce with advanced age despite their essential role in attentional and executive functions and short-term memory (Braver & Barch, 2002; S.-C. Li et al., 2001). Similarly, declining dopaminergic and cholinergic projections in the prefrontal cortex reduce parietal and Frontal Eye Field activity (Froudist-Walsh et al., 2018).

At the **vascular level**, higher blood pressure and reduced perfusion have been reported to induce increased effects of aging on brain structure (Goldstein et al., 2005). Researchers have also investigated cerebral circulation and oxygen metabolism (Yamaguchi et al., 1986) and showed a reduced regional cerebral metabolic rate of oxygen ($rCMRO_2$) with age.

At a **neuroanatomical level**, gray matter (particularly prefrontal, entorhinal, and temporal cortices) and white matter thicken with advanced age (Raz, 2000; Raz et al., 1997; Raz & Rodrigue, 2006), together with an increase in the ventricles size and the cerebrospinal fluid. Those structural changes induce cognitive alterations and cognitive compensations that are described further in this section.

Figure 3. *Schematic Representation of the Main Physiological Changes during Aging.*



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Fortunately, there is growing evidence from cognitive psychology, neurosciences, and biology that aging processes can also be adaptable and resilient. In that perspective, L. Aron et al. (2022) reviewed some major aspects of the brain that can be reinforced, protected, and 'restored' within a neurobiological scope (i.e., adaptation of the cellular metabolism, neural adaptations, neural networks adaptations, neurons-glia interactions, genetics, systemic adaptations), see also: Livingston et al. (2020) and Mora (2013) for broader reviews on successful aging.

Cognitive Models of Aging

To account for the changes observed in cognitive age-related experiments and daily-life observations, different theories were proposed: two-processes theories (Cattell, 1987; Craik & Bialystok, 2006), models of resources limitations (Craik & Byrd, 1982; Salthouse, 1996a), the dedifferentiation of cognitive functions (Lindenberger & Baltes, 1994), a general executivo-frontal hypothesis (West, 1996), and the more specific Dual-Mechanisms Control theory (Braver et al., 2007). These main cognitive changes and the major theoretical models proposed to explain cognitive aging are summarized in this section.

Models of the two processes.

One of the first cognitive theories about aging came from Cattell (1987) with the two-processes theory. Following his previous work on intelligence (Cattell, 1963), Cattell investigated the differentiated modifications due to aging between fluid and crystallized intelligence. The former includes reasoning, facing problems in new situations, and resolving them; it is the ability to solve novel situations and learn from them. The latter encompasses retrieving and applying previously learned knowledge to new situations, such as vocabulary, culture, and mathematics. Fluid intelligence declines sooner and faster than crystallized intelligence with advanced age (Ghisletta et al., 2012; Kievit et al., 2016). Later on, Craik & Bialystok (2006) later proposed a distinction based on two processes, the control and the representation functions (for a review, Gombart et al., 2018). The control function relies on the fluid intelligence represented in their model by working memory or by executive functions, as they have been defined in recent years in terms of multiple processes, inhibition, flexibility, updating, planning, and focusing of attention (Miyake, Friedman, Emerson, Witzki, Howerter, et al., 2000). The representation function relies on the knowledge and experience acquired throughout life, crystallized intelligence. Considering these two functions, the same pattern as for Cattell's model is expected regarding age-related decline: an increase in both functions until early adulthood with a specific decrease of control abilities starting in mid-adulthood. However, these models seem oversimplified and do not reflect inter- and intra- variability across the lifespan (Kievit et al., 2018), nor take into account the subcomponents and relationships between cognitive functions (e.g., long-term and short-term memory interactions or the different executive functions).

Models of resource limitations.

Models of resource limitations constitute a large field of research and explanations regarding age-related decline. **Craik & Byrd (1982)** suggest one of the oldest theories of resource limitations. Their model suggests that age-related declines in processing resources, such as processing speed or working memory, are likely responsible for general age-related decline. In 1996, Salthouse postulated that cognitive aging reflects a gradual slowing of processing speed and may be the primary contributor to the decline in cognitive functioning associated with aging. Indeed, a cognitive slowdown is observed during normal aging, associated with decreased processing speed, which is involved in many cognitive tasks. Thus, the cognitive slowing hypothesis suggests that the decline in processing speed is the most plausible general explanation for the decline in cognitive performance with advancing age. A slower processing speed involves a reduced possible number of cognitive operations in a given time and constitutes the so-called time-limited mechanism. Thus, older adults showing a significant decline in processing speed would have poorer cognitive and sensorimotor performance, whereas the effects of age would preserve those managing to maintain a good level of processing speed and show less memory decline.

Moreover, **Salthouse (1996)** proposed that the decrease in processing speed induced by a progressive nervous system deterioration would result in a quantitative and qualitative decrease in performance. Several studies (for a review, see Angel & Isingrini, 2015) have demonstrated the influence of processing speed on cognitive performance, such as arithmetic strategy initiation and reasoning. A slower processing speed is also a predictor of age-related decline, specifically in memory strategy initiation metamemory, prospective memory, episodic memory (McCabe et al., 2010; Nettelbeck & Rabbitt, 1992) and in working memory(Luria & Pribram, 1973) (Salthouse & Babcock, 1991). Eventually, Clarys et al. (2007) also showed that processing speed was one of the mediators of age effects in episodic memory but also on executive functions.

The hypothesis of the dedifferentiation of cognitive functions.

Lindenberger & Baltes (1994) explored the connection between auditory and sensory functioning with cognitive aging. They suggested that sensory (auditory and visual) abilities could be a late-life predictor of the individual differences observed amongst older adults (>70 years old). In their 1994 study, participants underwent fifteen tests targeting speed, reasoning, memory, knowledge, and fluency. Via structural modeling analyses, the authors showed that visual acuity and auditory acuities could be responsible for 41,3% and 34,6% of the total variance in intellectual functioning; vision and hearing could explain 49,2% of the total variance and 93,1% of the age-related variance. In **1997, Baltes & Lindenberger** also showed that this sensory factor is a better determinant of the effects of age than processing slowdown. However, the authors did not claim a conclusive distinction between a specific sensory decline and a cognitive/intellectual decline. They would rather claim a third theory: a common cause (general processing resources) hypothesis. According to their theory, the deterioration of the aging brain is associated with a decline in neural differentiation. Instead of the differentiation seen during development, this alteration in neural specialization would result in a phenomenon of increasing dedifferentiation of cognitive and sensory capabilities. This means that the specialized neural pathways that were well-defined and distinct during development start to lose their specificity and become less differentiated in older adults. In other words, the once well-defined and efficient neural circuits become less specialized and more generalized with age. The consequence of reduced neural differentiation is a phenomenon known as increasing dedifferentiation of cognitive and sensory capabilities. This implies that cognitive functions and sensory processing become less distinct and more interconnected in older individuals. As a result, the brain's ability to precisely process and differentiate various cognitive and sensory tasks diminishes.

Executive-frontal hypothesis.

The hypothesis of executive function deficits resulting from prefrontal dysfunction, put forward by **West in 1996**, has been proposed as an essential feature of cognitive aging, particularly memory aging (Isingrini & Taconnat, 2008; West, 1996). The central point of the frontal hypothesis is that the prefrontal cortex is going through an involution after full development. Therefore, neuroanatomical and neuropsychological changes happen when declining and are associated with age-related decline. Four years after West’s hypothesis, Raz (2000) confirmed that aging is specifically marked by reductions in gray and white matter volume, neuronal density, metabolic activity, and neurochemical modulation, particularly by the neurotransmitter dopamine. According to the executive-frontal hypothesis, "*cognitive functions supported by the prefrontal cortex should reveal declines at an earlier age that those supported by other brain regions*" (West, 1996; p. 272).

Additional assumptions of the executive-frontal hypothesis are that age-related effects would start earlier when related to the frontal functions rather than non-frontal functions. Older adults would have poorer memory performance than younger adults because the task would require greater executive effort. As previously described, executive functions are a set of high-level skills. In addition to the fact that they are a set of mental operations or processes, Rabbitt (1997) describes executive functions as useful for the formulation or identification of goals, planning, choosing between alternative sequences according to their possibility of success, or for the implementation of a selected activity, its modifications, and its completion. The executive-frontal hypothesis specifies that executive functions may be the first cognitive functions to decline with aging. Indeed, as mentioned in Chapter 1, executive functions are mostly underpinned by the prefrontal cortex (Luria & Pribram, 1973).

Another set of studies goes further and underlines the differential effects of aging within the different subregions of the prefrontal cortex. MacPherson et al. (2002) compared executive tasks supposed to be underpinned by the ventromedial PFC to tasks that the dorsolateral PFC underpinned. They found a discrepancy between both sets: age-related differences were found in the tasks involving the dorsolateral PFC but not systematically in the ventromedial PFC (see Figure 2).

Dual-Mechanisms Control Theory.

The Dual-Mechanisms Control theory (Braver et al., 2007; Gonthier et al., 2016) also attempted to explain the age-related decline in Executive Functions. Their model conceptualized reactive control as a conflict resolution mechanism. When no task-relevant information is available beforehand, attentional control is recruited just in time after a high-interference event is detected (Vadaga, s. d.). Proactive control is defined as goal-relevant information actively maintained in WM in a sustained or anticipatory manner (Braver, 2012). At the neuroanatomical level, reactive control would rather be associated with transient activations of the lateral PFC, whereas reactive control would be underpinned by sustained and/or anticipatory activation of the lateral PFC. The Dual-Mechanisms Control theory is interesting in aging as it accounts for intra and inter-individual specificity. Indeed, Braver (2012) explains that his model encompasses intra-individual (i.e., state or task-related), inter-individual (i.e., trait-related), and between-groups (i.e., related to changes in brain function or integrity in different populations). So far, this model and its assumptions mainly show age-related deficits in proactive control and age-equivalence in reactive control (Bugg, 2014; Tsang, 2013; Vadaga et al., 2016). However, older adults may compensate for deficits in proactive control by relying more on reactive control processes (Braver et al., 2009). Reactive control can still effectively handle unexpected situations or resolve conflicts, allowing older adults to maintain cognitive performance in certain circumstances. It suggests that age-related changes in cognitive control could involve a shift from proactive to reactive control strategies. Older adults may rely more on reactive control as a compensatory mechanism to maintain cognitive performance despite deficits in proactive control.

Integrative models of neurocognitive aging

Physiological changes have been shortly explained, from genetics to structural brain modifications, and the main models of cognitive aging have been reviewed in this chapter. By combining these physiological changes and cognitive conjectures, several theories account for neurocognitive aging. Four main models are summarized in this section, including the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH), the Hemispheric Asymmetry Reduction in Older adults (HAROLD) model, the Posterior-Anterior Shift in Aging (PASA) theory, and the Scaffolding Theory of Aging and Cognition (STAC and STAC-r). All those models share one common assumption: aging comes with a reorganization in brain mechanisms. See also McDonough et al. (2022) for a recent review.

CRUNCH, Compensation-Related Utilization of Neural Circuits Hypothesis model (Reuter-Lorenz & Cappell, 2008). This model proposes that task-level demands induce changes in the level or extent of brain activity. Thanked newer fMRI studies, the CRUNCH model also suggests higher activation rates in low task demands for older adults, whereas younger adults show higher activation in high task demands (Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Lustig, 2005; Reuter-Lorenz & Mikels, 2006). However, this supplementary recruitment would have a greater cost because older adults would exhaust their resources faster than younger adults because they got less (Cappell et al., 2010). In 2022, Kang et al. provided a short narrative review on inhibitory control in aging with regard to the CRUNCH model. According to the authors, decreased activities in brain regions usually associated with inhibitory control (i.e., inferior frontal gyrus) are compensated by increased activities in additional brain regions. They suggest that the CRUNCH hypothesis is better for understanding the changes in age-related activations in RI.

HAROLD, Hemispheric Asymmetry Reduction in OLDer adults model (Cabeza et al., 2002). This model underlines a shift in brain activations in older adults. More precisely, older adults would have more bilateral prefrontal activations compared a more unilateral activation in younger adults. Older adults would recruit additional brain regions to compensate for declining brain functions while performing the same task (episodic memory, working memory, semantic memory, visual perception, and inhibitory control) (Festini et al., 2018). This phenomenon is assumed to be an older adult's attempt to make up for cognitive deficiencies.

PASA, Posterior-Anterior Shift in Aging model (Davis et al., 2008). The prefrontal cortex becomes more active, and the occipital cortex becomes less active as we age, especially when doing cognitive and memory tasks (working memory, encoding, and retrieval in episodic memory). An age-related decreased activation in occipitotemporal regions and increased activation in frontal regions could indicate their efforts to compensate for their cognitive limitations (Ren et al., 2019; Zhang et al., 2017).

STAC(-r), Scaffolding Theory of Aging and Cognition (-revised) (Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014). The STAC model attempts to encompass the three previous models by integrating cognitive, structural, and functional evidence to explain cognitive and neurological alterations. Secondary neural networks would come into play to compensate for less efficient neural networks, following a scaffolding process: additional prefrontal and parietal regions and bilateral homologous or supplementary networks recruitment. The revised version of the STAC model encompasses longitudinal changes and life-course neural enrichment (e.g., physical activity, level of education, social interactions) and depletions elements (e.g., stress, isolation), factors potentially inducing physiological changes mentioned above.

Interference Theory

As briefly introduced in Chapter 1, Interference theory suggests that our ability to recall information depends not only on the strength of the memory itself but also on the presence of other memories that may interfere with it. According to early theories, there are two types of interference: proactive and retroactive. Proactive interference occurs when previously learned information interferes with the recall of new information, while retroactive interference occurs when new information interferes with the recall of previously learned information. For example, let's say you learned a new phone number yesterday and then tried to remember an old one today. If the new phone number interferes with your recall of the old one, this would be an example of retroactive interference. When following neurocognitive aging and the theories briefly explained above, one can easily suppose that inhibition will not be spared by age-related decline, especially when it is mainly supported by the prefrontal cortex, known to be among the most affected regions with age (Raz et al., 1997).

Following the historical line of the Interference theory, Hasher and Zacks (1979) proposed their "Inhibitory Deficit Theory." They assumed that decreases in the effectiveness of regulated or effortful processes cause age-related deficits in various cognitive areas. These authors have since clarified their argument, contending that one of the main factors causing age-related disturbances in higher-order cognition is a loss in the effectiveness of inhibitory mechanisms that allow one to limit the effects of task-irrelevant information (Hasher & Zacks, 1988). Note that this has led to a blurring use of the terms inhibition and interference and that both are often used interchangeably in theories of aging since then.

The inhibitory framework supposes a fast, accurate, and efficient "*mental life requires the ability to limit activation to information most relevant to one's goal*" (Lustig et al., 2007). It is well-known that inhibition is not optimal in young children as their prefrontal cortex is not completely mature until early adulthood. In older age, the inhibitory framework also postulates that inhibition is less efficient as the elderly act with more fatigue, less motivation, more stress, and circadian dysregulation (Hasher et al., 1999). To better understand the Inhibition Deficit Theory, its organization should be defined. Hasher & Zacks (1988) tried to organize inhibitory functions around three main processes: access, deletion, and restraint. One can refer to Campbell et al. (2020) for a complete review of these functions.

Access

The access function prevents irrelevant information from accessing the focus of attention. A deficit in access impedes the entry of irrelevant information into the scope of attention. Depending on the relationship between the distractors and the targets, deficiencies in accessing control allow distraction to affect how target stimuli are processed, sometimes by interfering and other times by supporting performance. In 1991, Connelly et al. initially investigated the impact of distraction on reading by comparing young and older adults. Both groups had to read aloud and answer questions about texts with distracting material. The Elderly took more time ignoring the stimuli irrelevant to the task than the younger group. It also seems to be the case for visual information. For example, Madden (1983) showed that older adults were slower and performed worse in detecting targets among distractors when the number of distractors increased. On the contrary, Vadaga et al. (2016) observed no age difference for the access function when using a Flanker task in which flankers were either ahead of the current target or unrelated. This last study joins a previous conclusion from Feyereisen & Charlot (2008), claiming that age-related differences are not uniform but vary depending on task-specific designs.

Deletion

The deletion function corresponds to deleting irrelevant information from the scope of attention. Typically, irrelevant information can be previously encountered information that is irrelevant, or that succeeded in going through the access function. Older adults tend to produce more irrelevant information with advanced age, suggesting a reduced ability to down-regulate no-longer-relevant information, as shown by Hasher et al. (1999). This phenomenon was also studied in direct forgetting procedures where participants had to forget some information to allow the right information to be remembered. Zacks et al. (1996) compared young and older adults in four direct forgetting tasks, with the different variations being: words lists categorized in exhaustive (1) or non-exhaustive (2) categories, in which a target was associated with a remember cue or a forget cue; or (3) with unrelated words presented in block, or (4) a mix between zero to four to-be-forgotten words followed by one to four to-be-remembered word. Overall, older adults presented more intrusions errors of to-be-forgotten items and took much longer to reject the to-be-forgotten items and recall and recognize more to-be-forgotten items than younger adults. The deletion function has also been studied in garden-path sentence completion tasks by Hartman & Hasher (1991), Hamm & Hasher (1992), and May et al. (1999). These tasks induce individuals to think of a very likely word before giving them a less likely word that completes a sentence and that they are supposed to memorize for a future memory test. Then, an implicit memory test is performed to assess the two potential sentence completions. Older adults tended to show broader and more sustained activation of alternative interpretations in addition to a lower level of recall. Charlot & Feyereisen (2004) also showed that priming was equivalent for recalled and inhibited words for older adults compared to younger adults for whom priming was higher for recalled than inhibited words.

Restraint

The restraining function corresponds to the suppression of goal-irrelevant dominant or habitual responses. Restraining irrelevant information is useful to withhold reading a word but naming the ink in which it is printed, like in the Stroop test (Stroop, 1935), or to not answering no-go trials in a Go/No-Go task. Age-related differences in restraining non-pertinent information have been suggested very early on. Butler et al. (1999) showed that older adults had more difficulties resisting prepotent reflexive ocular responses than younger adults in an antisaccade task.

In 2014, Pettigrew & Martin conducted a study on different aspects of interference resolution in aging based on the interference deficit theory of aging and the concepts brought up by Friedman & Miyake in 2004: resistance to proactive interference and response-distracted inhibition. One hundred two young adults and sixty older adults completed a Recent-negative task (with words), a Cued recall with direct forgetting task (with words), and a release from proactive interference task to assess resistance to proactive interference (with words). To assess response-distractor interference, participants underwent a Flanker (with letters) task, a picture-word interference task, a non-verbal (with arrows) Stroop, and a classical verbal Stroop. The results showed that older adults show age-related deficits in both interference mechanisms. Their analysis excluded confounding variables such as WM or processing speed, potential mediators of age-related deficits.

In summary, when responses are strongly stimulated by a familiar cue but cannot be produced, the restriction function will come into play (Grandjean & Collette, 2011). Hasher and Zacks believe working memory inhibition/RI deficiencies are key to cognitive aging. RI would, in fact, regulate the information in WM, preventing any unnecessary data from filling up its storage space. Therefore, retained inhibitory mechanisms would enable attention to be maintained on information pertinent to the job while preventing distraction from unrelated information. Age-related declines in RI abilities would unquestionably impair performance by allowing important information to overwhelm WM's constrained processing and storage resources. Surprisingly, there have not been many experimental studies done so far on this theoretical model that separates three RI processes that are directly related to WM. Thus, Charlot and Feyereisen (2004) demonstrated that being older had a negative impact on these three cognitive processes. However, the effect was less pronounced when the test used for information filtering involved working memory. A different study conducted by Dumas and Hartman (2008), however, was unable to demonstrate a negative impact of aging on the filtering and suppressing functions. The following section exposes some specifications about verbal and visual RI in aging.

What about Verbal and Visual RI in Aging?

Multiple theoretical accounts were proposed based on theoretical (Dempster, 1993; Hasher & Zacks, 1988; Nigg, 2000) and psychometric (Friedman & Miyake, 2004; Harnishfeger, 1995; Miyake, Friedman, Emerson, Witzki, Howerter, et al., 2000) work. Hasher and Zacks proposed that age-related RI decline influences other cognitive processes, such as working memory and, thus, episodic memory. In 2018, Rey-Mermet & Gade reviewed in a meta-analysis eleven RI tasks (i.e., the color Stroop task, the color-word Stroop test, the flanker task, the Simon task, the global–local task, the positive and negative compatibility tasks, the paradigm assessing n-2 repetition costs in task switching, the stop-signal task, as well as the go/no-go task) within a Bayesian approach (i.e., testing a RI deficit in older age and the absence of deficit with older age). Interestingly, their approach suggested (a) a need for more research on Simon task, global, and positive and negative compatibility tasks, (b) an absence of age-related decline in Stroop task, the color-word Stroop test, the flanker task, the local task, for the n-2 repetition costs; (c) and a clear effect of aging for the stop-signal and go/no-go tasks. In other words, it seemed that there is no general RI age-related decline. The authors also claimed for a better assessment of RI by designing paradigms properly comparing different constructs (e.g., motor coordination in some tasks and not in other), functions (e.g., deleting irrelevant information or restraining stimuli to access attentional scope), and domains (e.g., motor, visual, verbal). However, little research has been conducted on possible age-related effects in comparing cognitive domains such as visual and verbal RI.

Investigating the cognitive domains targeted by the different experiment would help researchers to understand better in what extent elderly are impacted (or not) in their visual/verbal RI abilities, in term of empirical findings, and not just in terms of theoretical constructs. It is to note that this field of research is quite narrow, especially for visual RI.

In the next section, data on visual RI and verbal RI in healthy aging will be shortly presented, followed by highlights on a specific condition acquired mostly with aging: aphasia.

Visual and Verbal RI in Healthy Aging

Visual and verbal RI in healthy aging is not a well-defined field of research, as studies and scientific literature mostly focus on RI functions and processes, as defined previously. Therefore, data must be dug out and examined with regard to the domain targeted by the tasks used, which is easier for verbal RI. Critically, verbal RI performances tend to decrease with advanced age. For example, in Pettigrew & Martin's (2014) experiment (see above section), almost all of the tasks targeted the verbal domain by using words (semantic RI) or letters (phonological RI), thus showing a decline in semantic RI with age.

Studies on normal aging have also contributed to the distinction between verbal and visual domains. Indeed, Guerreiro et al. (2010) carried out a study on aging and cognitive RI deficits. They found that interference was more likely to occur on unimodal tasks (e.g., visual task - visual interference) than transmodal (e.g., visual task - hearing interference). This study demonstrated an age-related difference in RI capacities depending on the perceptual modality (visual or auditory). The elderly showed greater sensitivity to interference in the visual modality than in the auditory.

Moreover, the elderly appeared to be more sensitive to visual interference, whether the task was unimodal or transmodal. Three years later, Guerreiro et al. (2013) did not find this exaggerated visual interference effect in elderly subjects on unimodal tasks, but they did on transmodal tasks. Although these results qualify those obtained in the 2010 study, they support the idea that the cognitive domain modulates RI capacities. Indeed, older adults were not more affected than younger people by verbal interference on cross-modal tasks, while they were affected by visual interference.

Even more specifically, Attout et al. (2022) investigated semantic and phonological RI control in a fMRI experiment with elderly participants. Following Rey-Mermet and Gade's (2018) advice, the authors used similar task designs and procedures to enhance task reliability and further theoretical considerations. Behaviorally, they observed a main effect of RI control for both accuracy and response times in the semantic domain and only for accuracy in the phonological domain. At the neuroanatomical level, multivariate analysis showed RI control effects in the fronto-temporo-parietal region for the semantic domain and in the pars triangularis of the bilateral IFG, and to the left MTG for the phonological domain. This hypothesis is consistent with the view of some authors that language disorders are caused by deficits in phonological and/or semantic RI (Hamilton & Martin, 2007; Jefferies et al., 2007).

🗐 Based on the following publication: Attout, L., **Grégoire, C**., Querella, P., & Majerus, S. (2022). Neural evidence for a separation of semantic and phonological control processes. *Neuropsychologia, 176*, 108377. https://doi.org/10.1016/j.neuropsychologia.2022.108377

To sum up, there are no better words than the ones from McDowd et al. (1995): "*However, a number of empirical and theoretical issues remain to be addressed. One important issue is the question of global versus specific deficits. An important contribution to theory building in cognitive aging would be "to tease apart the various types of interference and determine their specific contributions to age differences" (Dempster, 1992, p. 66)*" (p.396).

Insights from Neuropsychology: the Case of Aphasia

Regarding verbal RI, a strong distinction has been made between linguistic components from other cognitive components. However, Simic et al. (2019) underlined the integrity of executive control as a promising prognostic variable for language recovery abilities. They also highlighted the impact of control skills on language by taking the example of naming training: several studies suggested that better executive control skills would allow aphasic patients to learn more effectively from the facilitative strategies used in these exercises and generalize them to non-trained items. Nonetheless, in the aphasia literature, only a few studies have been reviewing the nature of executive functions deficits (Keil & Kaszniak, 2002; Purdy, 2002), and even fewer have researched the nature of RI deficits (Mohapatra & Marshall, 2020). Plus, as written by Majerus (2018), aphasic patients can have intact access to their representations, but they can have difficulties in resisting irrelevant language representations or deactivating language representations, leading to deficits in language and verbal tasks. Indeed, no-longer pertinent representations that are still activated will interfere with the target content, thus creating confusions and intrusions errors (Biegler et al., 2008; Nozari, 2019).

In 1996, R. C. Martin and Lesch investigated language and short-term processes within three aphasic patients: patients A.B., M.L., and M.S., who got lesions in their left hemispheres. Among other tasks, all three performed a repetition task of word lists of increasing length. They made many omissions, formal and phonological paraphrases, and semantic descriptions for M.S. only. In addition to these errors, A.B. and M.L., who had a deficit in semantic working memory, made a significant proportion of errors involving the intrusion of words belonging to previous lists. On the contrary, M.S., who had a phonological working memory deficit, made only one intrusion error on the entire test. The authors concluded that a buffer should be between the information codes maintained in working memory and the language representation system. In this buffer, competition among different item codes and item traces appears. To get a good recall in short-term memory, we assume a specific process interplays to shut down the competitor's codes and traces, cognitive RI.

In 2002, Thompson-Schill et al. investigated the effects of frontal lobe lesions on interference effects in working memory depending on the injury location. One patient, R.C., presented with a lesion in the anterior part of the left middle and inferior frontal gyri. This lesion impinged on the region linked to interference effects. Compared to six patients with posterior or superior lateral prefrontal cortex lesions (five left, one right), patient R.C. exhibited more interference effects on both response time and accuracy. The authors suggested that the left inferior frontal gyrus accounts for more general cognitive control. Although they considered the LIFG as implied in a nonmnemonic selecting process, there is also important controversy, especially when compared to D'Esposito and Postle (1999). Their meta-analysis concluded that frontal damage was more likely to disrupt RI processes in working memory tasks.

Nevertheless, carefulness is needed regarding two aspects. The first aspect is the localization of the different lesions. D'Esposito and Postle (1999) grouped many patients in their analysis, erasing each individual's specificity. The second aspect reflects the lack of precision concerning the material (i.e., letters, numbers, sentences) and the tasks (go/no-go, blocked cyclic naming, WM) manipulated in the different studies.

Studies in aphasia provide an additional factor to consider beyond the general debate about the generality or specificity of cognitive RI. These studies focus on the dissociation between a broad semantic impairment and a deficit in semantic control. Depending on the specific tasks employed or the location of the brain lesion, the interpretation of the results consistently supports this notion. Even if the question had already been raised by Martin and Lesch (1996), it was after 2000 that different authors took a real interest in this distinction. Jefferies and her team (Jefferies et al., 2007a; Jefferies & Lambon Ralph, 2006a) examined semantic RI impairment. In 2006, they compared ten patients with semantic dementia and ten aphasic patients on the same semantic tasks. Results showed that both groups failed almost the same semantics tasks globally linked to verbal and non-verbal comprehension.

Nevertheless, these results do not reflect the same processes: patients with semantic dementia underwent amodal semantic deficits resulting from degradation in the anterior temporal lobe, while aphasic patients underwent semantic RI deficits resulting from their fronto-temporo-parietal lesion. In 2007, Jefferies et al. kept examining the effects associated with the semantic access impairment observed in their 2006 study: speed of presentation, item repetition, semantic blocking, inconsistency and absence of frequency effects, and facilitation by cues, also called refractory effects. Findings indicated that patients presented at least one of these effects, plus effects of cueing, the absence of frequency effects, and test-retest consistency. It is to be emphasized that these effects are weaker within patients who got temporoparietal lesions compared to aphasic patients with LIFC lesions. The authors also compared aphasic patients' data to a patient with semantic dementia, who showed no features of a semantic access impairment and a pronounced degree of test-retest consistency. Thus, this study postulates that the semantic deficits found in aphasic patients reflect a disorder of semantic control (and not an unpredictable failure of semantic access).

To sum up, difficulties encountered by aphasic patients with left inferior frontal cortex lesions may result from controlling activation deficits within their semantic system, thus, in semantic RI abilities. This aligns with Schnur et al. (2006) results, which showed that aphasic patients with a left inferior frontal lesion had increased naming error rates and slower naming latencies. It could result from increased activation of competitors slowing naming processes due to a lack of semantic RI induced by the lesion /disruption of the selection mechanism. Biegler et al. (2008) also observed this semantic blocking effect (i.e., increased error rates and decreased latencies) in two non-fluent aphasic patients, M.L and B.Q. However, they performed similarly to the group control on associated word-picture naming tasks. These results indicate a contrast between comprehension and production skills for both patients, explained by the authors as difficulties in postelection inhibition. Indeed, the number of lexical representations elicited by the different stimuli is not sufficiently inhibited, causing difficulties in selecting the relevant stimuli for the situation. Eventually, Tan & R.C. Martin (2018) showed that aphasic patients were globally more prone to semantic and syntactic interference. However, only semantic interference was correlated with semantic STM memory performance, while syntactic interference was correlated with their executive functioning abilities. The authors suggested that different sorts of active information degrade at various rates when it is not the focus of attention (e.g., semantic, syntactic, phonological); therefore, RI.

Beyond examining the semantic RI defect, we can explore a dissociation between phonological and semantic RI. In 1999, Poldrack et al. shed light on differences within the verbal domain by distinguishing phonological RI and semantic RI while studying the main identified cerebral region: the left inferior prefrontal gyrus in a group of healthy adults. Their findings revealed a greater activation in the dorsal left inferior prefrontal region during phonological processing and a greater activation in the ventral left inferior prefrontal gyrus during semantic processing. Furthermore, they suggested that the ventral part may be specifically involved in semantic processes only, while the dorsal part may play a role in more general phonological processes.

Hamilton and Martin (2007) investigated the role of phonological and semantic traits in proactive interference in working memory through a group of older adults and an aphasic patient, patient M.L. Authors suggested that this proactive interference is rather the result of an RI deficit that causes an abnormal persistence of traces in WM, leading to a competition between semantically related codes. Furthermore, M.L. had difficulty resisting both semantic and phonological representations. In other words, aphasic patients with a semantic memory deficit generally also have an impairment (albeit to a lesser extent) in phonological representations. However, the RI deficits would appear with any verbal information. On the other hand, the phonological memory deficit would be more specific and lead to a rapid loss of phonological information only. Barde et al. (2010) also investigated phonological and semantic RI within a recent-negative task with 20 aphasic patients and matched controls. They observed that control older adults were interfered in both phonological and semantic tasks, whereas aphasic patients were interfered in relation to their specific WM deficit. In other words, patients with weaker phonological WM also got more difficulty resisting phonological-related items, and the same was true for patients with weaker semantic WM. These results suggest that phonological and semantic RI may be distinct processes.

According to a recent study (Nozari, 2019), a deficit in access to information would be observed either in activation or inhibition deficit. Therefore, each of these mechanisms can be specifically altered. The fragility of the links between semantic characteristics and lexical representations would cause a deficit in activating semantic items. In addition, an inhibition deficit is due to difficulties in suppressing concurrent activated information (i.e., the ability to suppress information that has become useless or distracting to perform a given task). Finally, these results suggest a critical role for verbal RI in lexical selection.

For a long time, research supporting the major role of language processing also tends to show an implication of RI, either phonological or semantic, as mentioned above. Kuzmina and Weekes (2017) investigated verbal and non-verbal RI with 17 fluent aphasic patients and 14 non-fluent aphasic patients (see Table 1) via a non-verbal Flanker task, a verbal Stroop test, an auditory control task, and a domain-general cognitive control task. General results showed that aphasic patients were more impaired in verbal tasks than nonverbal ones. Non-fluent aphasic patients performed less in the domain-general control task and the demand-general part of the auditory control task. This was also confirmed by a correlation between verbal and non-verbal scores, whereas fluent aphasic patients only showed correlations within the verbal tasks. It provides evidence to underline different RI processes: on the one hand, all aphasic patients indeed have verbal RI impairment; on the other hand, only non-fluent also have a broader RI impairment. This study suggests that another distinction should be made between fluent and non-fluent aphasic patients, but it is rarely the case when studying and re-educating RI.

Table 1

Altered and Preserved Verbal Abilities in Aphasic Patients.

Studies	Patients	Lesions	Altered performances	Preserved performances
N. Martin & Saffran (1992)	Patient N.C.	Left middle cerebral artery aneurysm	Semantic errors in repetition and comprehension, imageability effects in lexical decision, ability to repeat nonwords	phonological discrimination is good in a minimal pairs judgment task
R. C. Martin & Lesch (1996)	Patient A.B.	left frontal + anterior parietal	Retention of semantic information	
	Patient M.L.	Left frontal + parietal operculum and atrophy left temporal operculum		Normal effect of phonological similarity. Slight advantage for auditory presentation over visual presentation
	Patient M.S.		Naming	Retain input phonological representations and semantic of the items
Thompson-Schill et al. (2002)	Patient R.C.	Anterior left middle and inferior frontal gyri	Sensibility to interference due to a ↘ semantic RI	
	6 Patients	Posterior or superior lateral prefrontal cortex (5 left, 1 right)	↘ baseline working-memory performance	= magnitude of the interference effect

Schnur et al. (2006)	18 patients	16/18 left inferior FC	↘ Semantic RI	/
Jefferies & Lambon Ralph (2006)	10 Patients	7/10 left (inferior) frontal lesions 8/10 left temporoparietal lesions	↘ Semantic RI	
Jefferies et al. (2007)	8 patients	6/8 LIFC lesion 2/8 temporoparietal lesion	↘ Semantic RI	
Hamilton & Martin (2007)	Patient M.L.	Superior LIFG and parietal operculum, + atrophy in the left temporal operculum, and mild diffuse atrophy	persistence of phonological and semantic representations	/
Biegler et al. (2008)	Patient M.L.	Left inferior and middle frontal gyri and large lateral areas of the superior and inferior left parietal lobe	Difficulty in post-selection RI	

	Patient B.Q.	Left frontal, parietal, and temporal regions		
	Patient K.V.	unknown		
Barde et al. (2010)	20 aphasic patients	left cerebrovascular accident	↘ Semantic RI when semantic STM ↘ ↘ Phonological RI when phonological STM ↘	
Kuzmina & Weekes (2017)	17 Patients (fluent)	18 Left middle cerebral artery 13 Left cerebrovascular accident	↘ Verbal RI	no impairment in the non-verbal
	14 patients (non-fluents)		↘ Verbal RI ↘ Domain-general RI	no impairment in the non-verbal
Tan & R.C. Martin (2018)	9 patients	left (only): IFG, MFG, lateral parietal, occipital, STG, PPG, insular, posterior parietal & left temporal	↘ Semantic and syntactic RI	
Nozari (2019)	Patient X.R.	right dorsolateral, superior temporal gyrus	Activation deficit	RI
	Patient Q.D.	left frontal and parietal lobes with some extension to the superior temporal gyrus	RI deficit	Activation
McCall et al. (2022)	32 patients	left hemisphere	↘ control	

Regarding visual RI, even though many studies exploring verbal RI in aphasia were run, almost none examined visual RI. Despite it, several works about aphasia support the idea that cognitive aspects should also be evaluated through visual aspects. For example, Hallowell (2008) underlined the need for a better evaluation and control for visual acuity, color perception, visual attention, and ocular motor abilities in aphasic patients. This need for a better evaluation should be extended to visual RI. Particularly, to what extent the visual inhibitory system does contribute to the preservation or deficit is unclear. Swick et al. (2008) investigated the role of the left IFG with a Go/No-Go (letters) in patients with a lesion in the frontal lobe. Thus, they were not necessarily aphasic. They showed that patients with a left IFG lesion were more affected in the No-Go condition as they demonstrated a higher rate of false alarms responses (i.e., answering when they should not) than patients with a lesion in the orbitofrontal cortex or controls. So far, the only modality-specific experiments in which aphasic patients exhibited a visual impairment are focused on optic aphasic patients (Beauvois, 1982; Marsh & Hillis, 2005; Plaut, 2002) – meaning they are unable to name visually presented objects but able to name them when presented in another modality. To sum up, there is still a gap in the literature regarding visual inhibitory assessments and their relation to other cognitive constructs in aphasia studies.

To our knowledge, no other study has investigated the specific contribution of different domains to tasks performances in the aphasia literature, except in optic aphasia or specific reeducation therapies such as the Visual Action Therapy for global aphasia (Helm-Estabrooks et al., 1982). Patients suffering from global aphasia neither produce nor comprehend speech or writing. Visual Action Therapy intervenes here through a nonverbal modality that led to a trend toward significant improvement in the ability to read noun and verb stimuli for some language subtests. Additionally, Conlon and McNeil (1991) confirmed an increased performance in the trained behaviors, even if it does not seem to generalize in improved communication skills. Kendrick et al. (2019) compared a verbal Stroop test and a verbal Flanker task to their nonverbal versions. Results showed that aphasic patients were generally slower than the control group. Even if the authors highlighted overall slower performances (i.e., an increase in response time), aphasic patients did not show a stronger interference effect as the magnitude of the differences between task type and condition (verbal and nonverbal) did not significantly differ. Kendrick et al. (2019) postulate that aphasic patients with frontal lesions rely on their executive control resources (inhibition, switching, and updating) regardless of whether the task stimuli are verbal or nonverbal.

In sum, these neuropsychological studies provide evidence for a distinction between phonological RI and semantic RI, which suggests that both systems can have specific impairments. However, the literature lacks evidence for visual RI or a distinction between verbal/visual domains. Deeper investigations would be needed to understand how these processes influence aphasic patients or language processing in general.

Chapter Summary

"***What now is the status of the inhibitory deficit hypothesis of cognitive aging?***" (McDowd et al., 1995, p.394). This chapter examined the different theories about cognitive aging through physiological changes, cognitive and integrative models, and, more specifically, within the scope of the Interference Theory. We also reviewed a few empirical works investigating visual and verbal domains with advanced age. The results appear far from clear-cut; while some studies showed some age-related RI deficits, others found weak evidence for an RI age decline. Considering the integrative models of cognitive aging, interpreting such results is difficult: Do they reflect a compensatory mechanism? Are they task-dependent? Or, Are they domain-dependent? Although we have reviewed a few results in healthy aging and aphasia, the results are not even clearer. However, it should be emphasized that the different methodologies used in neuropsychological studies do not allow for a straightforward conclusion. Therefore, this thesis aims to assess whether RI decreases with advanced age by manipulating visual and verbal cognitive RI and to determine the underlying neuroanatomical components. From that perspective, we will compare two different paradigms with visual, semantic, and phonological domains in healthy young adults and older adults.

Experimental Part

Objectives and Hypotheses

Although many studies have focused on RI from a cognitive, neural, or neuropsychological perspective, the nature of RI and its domain-specificity vs. domain-general character remain poorly understood. The data reported in the current literature are difficult to interpret due to very diverse tasks across different RI domains, raising the possibility that observed domain-specific RI effects are due to task differences rather than domain differences. Furthermore, very few studies have systematically compared RI across different domains, such as phonological, semantic, and visual domains. Most studies have focused on visual versus verbal domains, confounding phonological and semantic aspects. A further important debate concerns whether RI and its related brain networks decrease with advanced age and to what extent this decrease is domain-general or domain-specific. This PhD thesis aims to systematically compare RI across phonological, semantic, and visual levels by using structurally similar tasks across domains and a convergent behavioral, neuroimaging, and neuropsychological approach to investigation.

In Study 1, we conducted a focused mini-review on the specific aspects that will be further investigated experimentally in Studies 3 and 4. This mini-review examined the state-of-the-art regarding the domain-specificity of RI processes by including relevant cognitive, neuroimaging, and neuropsychological studies. It focused on visual, phonological, and semantic RI processes and, more precisely, their associations and dissociations at behavioral and neural levels, including aging and other neuropsychological study designs.

Study 2 was an experimental study preparing the materials for Study 3 and Study 4. More specifically, this study aimed a collecting emotional valence, concreteness, and imageability ratings for the stimuli to be used in the semantic RI tasks in the subsequent studies. It was necessary to run this preparatory study due to the limitations of current databases of the French language regarding these essential psycholinguistic dimensions for appropriate stimulus matching between RI and control conditions of the tasks used in Study 3 and Study 4. Study 3 simultaneously provided concreteness, imageability, and emotional valence ratings for 342 items, comprising 165 verbs and 177 nouns.

Study 3 assessed the domain-generality/specificity of RI capacity in young and elderly adults across phonological, semantic, and visual domains, using two different tasks across the three domains. The first task used in this study was a similarity-judgment task allowing for variable interference buildup. It involved judging which of two test-items was closest to two target-items, and each trial was preceded by a prime stimulus that pre-activated specific semantic, phonological, or visual features. In the RI condition, the features defining the prime stimulus pre-activated the incorrect test-item causing interference, while in the facilitation condition, the prime stimulus pre-activated the correct test-item. This task, initially developed for measuring semantic RI (Snyder et al., 2007), was adapted for measuring semantic, phonological, and visual RI. The second task was based on the recent negatives task (Barde et al., 2010) measuring RI in a working memory context. In this task, a sequence of stimuli is presented for memorization, followed by positive or negative probes. The negative probes are of interest for this study because they are either neutral or differ minimally from one of the stimuli of the (current or previous) memory list. These probe stimuli create interference due to their similarity with the target stimulus. The task was initially developed to assess semantic and phonological RI, and we adapted it further to assess visual RI. In this study, using group comparisons and the Bayesian ANOVA approach, we aimed to determine whether age effects on the RI measures within each task varied as a function of the task domain (phonological, semantic, visual). Additionally, a correlational analytic approach was used to examine whether RI abilities in one domain or task could predict RI in another domain or task or not. In summary, this study investigated the effects of aging on RI abilities across three domains employing two different tasks to eliminate task-specific effects.

Study 4 systematically investigated the neural substrates associated with RI abilities across phonological, semantic, and visual domains and their age-related changes. We used the same similarity-judgment task as in Study 3 for probing the neural substrates associated with RI across the three domains. We conducted a particularly exhaustive investigation of the neural substrates of RI, by assessing RI across the three domains with structurally closely matched task designs, by determining the overlap and differences of neural substrates associated with RI across the three domains as a function of age group (young adult vs. elderly participants), and by assessing both univariate and multivariate neural signals associated with RI. Neuroimaging studies focusing on RI have used mainly univariate analysis methods so far. Multivariate methods are much more powerful and sensitive as they allow us to determine the representational quality of neural activity patterns and not only differentially elevated activity peaks. This is a critical asset of our study as it allows us to determine whether areas potentially showing common RI-related univariate effects in the three domains of investigation also represent the same information and processes across the three domains.

Finally, the results of our studies will be discussed in light of current models of RI/cognitive control as well as theories of cognitive and neural aging.

Resisting visual, phonological, and semantic interference – same or different processes? A focused mini-review

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Abstract: The unitary nature of Resistance-to-Interference (RI) processes remains a strongly debated question: are they central cognitive processes, or are they specific to the stimulus domains on which they operate? This focused mini-review examines behavioral, neuropsychological, and neuroimaging evidence for and against domain-general RI processes by distinguishing visual, verbal phonological, and verbal semantic domains. Behavioral studies highlighted overall low associations between RI capacity across domains. Neuropsychological studies mainly report dissociations in RI abilities between the three domains. Neuroimaging studies highlight a left vs. right hemisphere distinction for verbal vs. visual RI, with furthermore distinct neural processes supporting phonological versus semantic RI in the left inferior frontal gyrus. While overall results appear to support the hypothesis of domain-specific RI processes, we discuss a number of methodological caveats that ask for caution in the interpretation of existing studies.

Keywords: RI; interference; domain-general; domain-specific; inferior frontal gyrus

Introduction

Resistance to interference: some definitions.

Resistance to interference (RI) has been defined as "*the ability to ignore or inhibit irrelevant information while executing a plan*" (p.397) (Dempster & Corkill, 1999). Harnischfeger (1995) made a critical distinction between inhibition and RI by proposing that the latter prevents irrelevant information from entering the mental workspace while the former involves active removal of information no longer useful for the current task. RI was initially defined as a property of memory processes. The Classical Interference Theory (McGeoch, 1932) claimed (McGeoch & Underwood, 1943; Melton & Irwin, 1940; see Demonty et al., 2022 for a recent review on interference and forgetting) that we are less likely to remember and recall an item (item A) if associated with a retrieval cue (item B) that has been paired with another item (item C) during the maintenance period. Item C is considered to interfere here with the maintenance and correct retrieval of item A (Müller & Pilzecker, 1900), a situation illustrating reactive RI. Next, the concept of resistance to proactive interference (Neoclassical Interference Theory ; Postman, 1961; Postman & Underwood, 1973; Underwood & Ekstrand, 1966) was introduced to characterize the situation when pre-existent information (so-called 'extra-experimental sources of interference') is interfering with novel information to be learned. In 2000, Nigg further distinguished RI from other inhibitory-related processes by proposing that RI prevents competition and/or distraction between stimuli and/or resources in order to maintain a certain level of performance. In 2004, Friedman and Miyake specified three different types of RI: resistance to distractor interference (i.e., to resist interference created by irrelevant stimuli while performing a task), resistance to proactive interference (i.e., prevent intrusions [into memory] by stimuli that were previously relevant but are no longer relevant), and prepotent response inhibition (i.e., the ability to purposely suppress dominant, automatic, or prepotent responses).

Domain-General and Domain-Specificity of Resistance to Interference.

While there has been ample interest in the definition of different, context-dependent types of RI, a fundamental question that has received less explicit consideration is whether these different processes are central processes or whether they are specific to each stimulus domain. In other words, is (proactive, distractor-related, …) resistance to irrelevant auditory-verbal or visual stimuli supported by the same general processes or are these processes specific to the representational properties of each domain, with the further possibility of the existence of domain-general and domain-specific processes at the same time? While RI is often considered to be a central, executive control process (De Baene et al., 2015; Green, 1998; Miyake, Friedman, Emerson, Witzki, & Wager, 2000), some authors have considered that RI may need to be distinguished according to the stimulus domain towards it is applied. Dempster (1993) identified perceptual RI for resisting to auditory or visual stimuli like sounds or symbols and distinguished it from linguistic RI (resistance to relevant linguistic units such as words or sentences) and motor RI (resistance to irrelevant motor acts such as pushing a specific button). In some types of computational models, RI is indeed modelled as a processing property of the representational systems themselves: once a stimulus has been activated/recalled, it is immediately deactivated via algorithms embedded in the representational layers (Oberauer et al., 2012; Schneider, 1993; Schneider & Detweiler, 1988). This makes sense given that interference rather occurs between stimuli from the same domain than between stimuli from different domains, hence within-domain control of interference is a particularly important cognitive process (Oberauer et al., 2012). In contrast, other models of RI and inhibitory-like processes have focused on a hierarchical organization of executive control processes without distinguishing domain specific RI processes (Frank et al., 2001; O'Reilly et al., 2010; Wiecki & Frank, 2012). Furthermore, some models of cognitive control consider the co-existence of domain-specific and domain-general control processes and make a distinction between "primary" and "secondary" controllers. This type of models considers that visual perception, language or motor domains may have their own primary controllers, while secondary (central) controllers operate, moderate, inhibit, and synchronize primary controllers (Verbeke & Verguts, 2021; Verguts, 2017b, 2017a). The question of domain-general and domain-specific RI processes is a central question for the theoretical modelling of RI as the answer to this question will determine whether RI processes should be directly integrated into the processing properties of specific stimulus domains, ~~or~~ whether they are better modelled as stimulus-independent, central control mechanisms, or whether both types of situations need to be considered.

Domain-General or Domain-Specific Interference: A narrative literature review

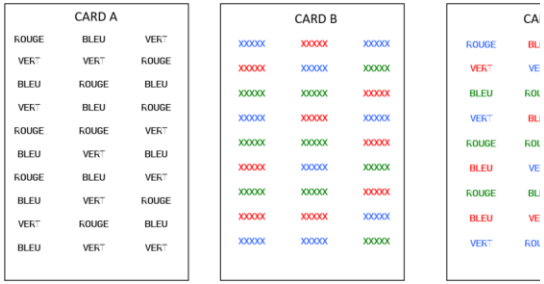
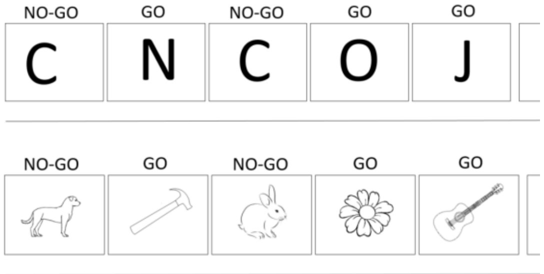
The aim of this review paper is to examine behavioral, neuropsychological and neuroimaging empirical evidence for and against domain-general RI processes. While distinguishing verbal versus visual domains, we will also distinguish phonological and semantic subdomains within the verbal domain given that there is ample behavioral, neuropsychological and neuroimaging evidence for a separation of these two representational domains (Gorno-Tempini et al., 2011; Patterson et al., 1987). We hypothesize that, if RI are domain-specific, i.e., directly embedded within the representational domains on which they operate, then a separation of RI capacity for visual versus phonological versus semantic information should be observable. Alternatively, if RI processes are (also) domain-general, medium to strong associations for RI capacity across domains should be observable. We reviewed behavioral, neuropsychological and neuroimaging studies in the light of these two main hypotheses. More specifically, for behavioral studies in healthy participants, we targeted studies that used an interindividual differences approach and compared RI across domains while probing the same type of RI (for example, verbal proactive vs. visual proactive). In case of domain-general RI processes, RI performance in one stimulus domain should correlate robustly with RI performance in the other stimulus domain (note that this outcome would not rule out the possibility of *additional* domain-specific RI processes); no or little correlation would be in favor of domain-specific RI processes. Importantly, we were not interested in examining whether there is cross-domain interference or not as this question would not necessarily inform us about the domain-general and/or domain-specific nature of RI processes. On the one hand, it could be argued that if RI processes are domain-specific, cross-domain interference effects should be smaller than within-domain interference effects for comparable tasks and material. However, it can also be argued that interference effects are intrinsically smaller when crossing domains because the stimuli are less similar and hence less prone to interference (Logie et al., 1990; C. C. Morey et al., 2013; Shah & Miyake, 1996; Vergauwe et al., 2010). We therefore decided to focus exclusively on studies examining whether the capacity to *resist* interference in one stimulus domain (e.g., visual Stroop task) determines (correlates with) the capacity to *resist* interference in another stimulus domain (e.g., auditory-verbal Stroop task) or not. We will use the same rationale when examining neuropsychological studies, but by focusing on associations versus dissociations of deficits in RI for visual vs. phonological vs. semantic-RI tasks. Regarding neuroimaging studies, we will examine the neural substrates associated with RI in different domains and then focus on studies that have compared RI across domains for comparable tasks and RI types. Finally, note that in order to ensure that we are comparing RI between clearly distinct domains, we will not include studies that compared RI for auditorily versus visually presented verbal material. We consider that presenting words auditorily or visually amounts to processing verbal information in both cases, and hence remaining mostly within the same stimulus domain; this situation would thus not be theoretically informative about the question of domain-specific and/or domain-general RI processes.

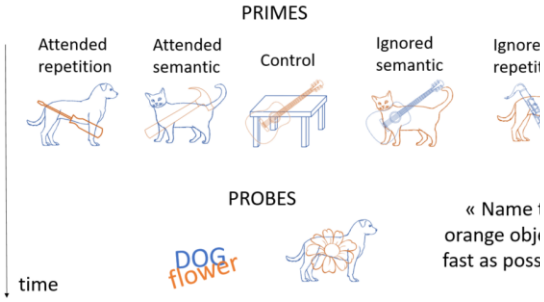
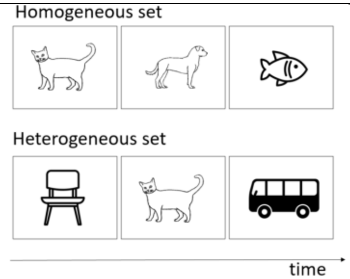
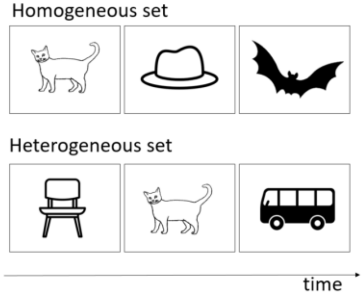
We used the following literature search strategy for this focused, narrative review. We first searched in the Medline-PubMed and APA PsychInfo databases studies listed with the following keywords (task-name[1]) AND (visual OR verbal OR (domain-specific) OR (domain-general) OR (modality-general) OR (modality-specific) OR semantic OR phonological) AND (interference AND ((resistance) OR (inhibition) OR (control)))) AND NOT motor), without any language restriction (but the title had to be translated in English). Only peer-reviewed empirical papers were included. Papers were then screened according to the specific search questions and research designs defined in the previous paragraph, and only studies corresponding to the specified research designs were retained. Additional relevant references cited in the examined papers that did not show up in the initial literature search were also included (see Appendix).

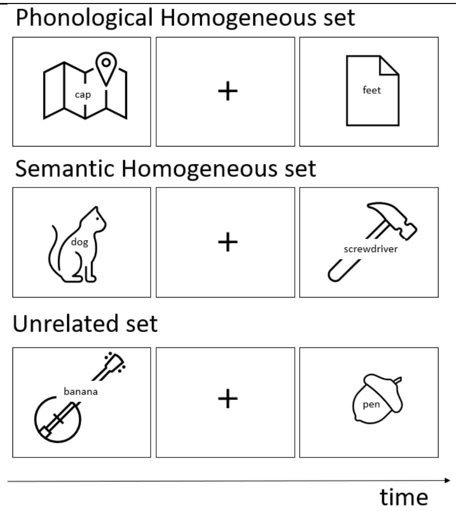
[1] As task-names, we introduced the names of very common tasks measuring RI or RI-related processes such as “Stroop”, “Flanker”, “Go/No-Go” task.

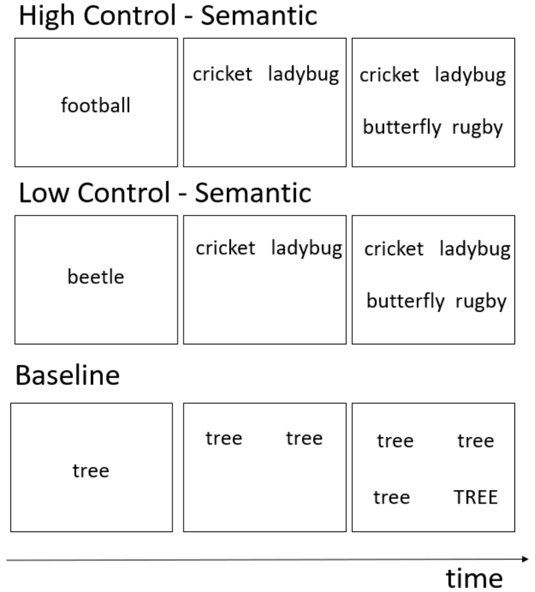
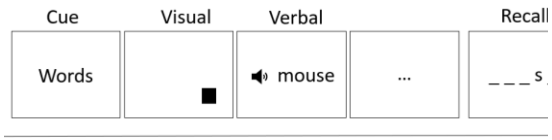
Table 1

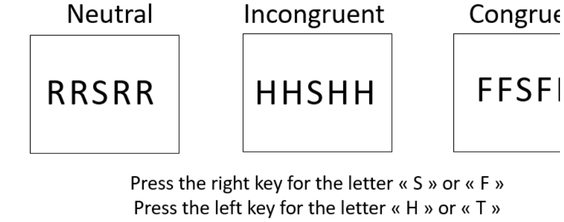
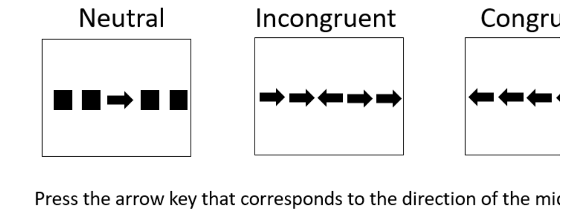
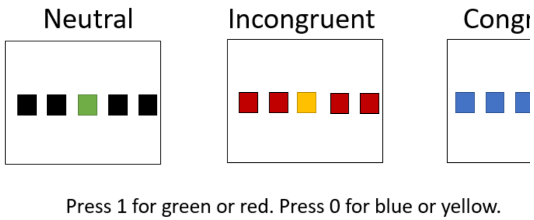
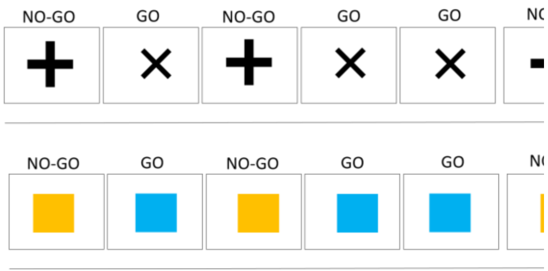
Description of verbal and visual RI tasks cited in this review.

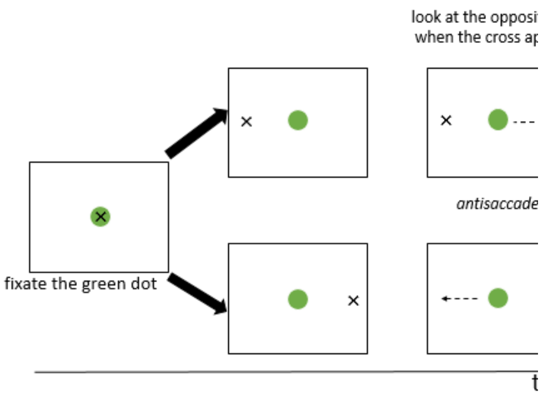
Task	Source	Type of RI	Stimuli (examples)	Description	Main effects	Domains
Stroop	Stroop (1935), Parris et al. (2022)	Interference caused by conflict between font color and word reading		Naming of the color font as quickly as possible	Increased naming latencies in the incongruent condition (CARD C) compared to the congruent condition	Verbal
Verbal Go/No-Go		Interference between target and non-target stimulus status		Pressing a key as quickly as possible for a specific word/letter/semantic category (Go condition) and ignore all other stimuli (No-Go condition))	More commission errors and slower response times for No-Go trials	Verbal

Negative -priming task	Tipper (1985), (2001); Tipper & Cranston (1985); Tipper & Driver (1988)	Interference caused by the change of stimulus status: a distractor stimulus becomes a target stimulus		Naming objects in orange font as quickly as possible	Increased reaction times and error rates for a target that had to be ignored in a previous trial	Semanti c
Semanti c blocked cyclic naming	Schnur et al. (2006); Schnur et al. (2009)	Build-up of semantic interference		Naming the pictures as quickly as possible	Slower response times and increased error rates when the repeatedly presented objects are from the same semantic category	Semanti c
Phonolo gical blocked cyclic naming	Damian, 2003; Hodgson et al., 2005	Build-up of phonological interference			Slower response times and increased error rates when the repeatedly presented objects are phonologically similarly	Phonolo gical

Picture-Word Interference	Glaser & Düngelhoff (1984)	Build-up of phonological and/or semantic interference		Name the pictures as quickly and accurately as possible while ignoring the superimposed words	Slower response times and increased error rates for related distractor	Verbal

Similarity-Judgement Task	Attout et al. (2022), Snyder et al. (2007)	Build-up of phonological and/or semantic interference	 	Choose which word at the bottom of the screen is most similar to the two words at the top of the screen, as quickly and accurately as possible.	Slower response times and increased error rates in the high control conditions as the prime word induced interference.	Verbal
Dual-Interference Task	Pashler (1994)	Build-up of verbal or visual interference	 	Concurrently and alternatively process two types of information. The tested condition (here, verbal) can be cued or uncued.	Increased error rates and longer reaction time in the tested condition (here, verbal)	Verbal and/or Visual

Flanker task	Eriksen & Eriksen (1974)	Response interference	  	Pressing of a response button according to a predefined response setup. This target can be flanked by a stimulus requiring the same or a different response as the target.	Increased reaction times if target is flanked by an item requiring a different response (interference) and reduced reaction times if target is flanked by an item requiring the same response (facilitation)	Verbal Visual
Visual Go/No-Go		Resist to a visual stimulus		Participants have to press a key as quickly for target symbols (e.g.,✕), (Go condition), and ignore all other stimuli (No-Go	More commission errors and slower response times for No-Go trials	Visual

				condition).		
Antisaccade	Adapted from Noorani (2014)	Resist to visual stimulus		Participants have to fixate a central stimulus and keep fixating the stimulus (green dot). Next a target (the cross) appears to the left, or the right of the dot and participants have to make an eye saccade to the opposite side (=antisaccade).	More errors/slower eye movements for antisaccade trials	Visual

Behavioral studies comparing verbal and visual RI in healthy participants.

Many studies have investigated RI in verbal or visual domains, but very few studies have directly compared RI performance across the two domains. Three studies were identified that corresponded to the search criteria. Morey and Mall (2012) investigated RI at the task level, by comparing performance for serial order reconstruction tasks for verbal or spatial stimuli, to be carried out in single-task or dual-task conditions. In the dual-task conditions, either both verbal and spatial stimuli (uncued condition), or only one of the two types of stimuli (cued condition) had to be maintained and recalled. While in the dual uncued conditions, a moderate-size correlation (r = .35) was observed between verbal and spatial recall measures, this was not the case (r = .18) in the cued conditions. The cued condition is the most informative here for the question of RI capacity given that this condition is not affected by between-stimulus competition for working memory maintenance (which could explain the correlation in the uncued condition) and RI is needed for selectively maintaining the cued visual or verbal stimuli. Oberauer et al. (2004) also investigated RI capacity across domains by using dual-task working memory paradigm. Oberauer and colleagues presented a list of verbal/visual items followed by a list of visual/verbal items in the dual-task condition, and only one type of list in the single task condition. Participants were then asked to recall one of the lists, a situation similar to the cued condition in the study by Morey and Mall. The authors computed different measures of dual-task interference costs (e.g., subtracting the dual-task score from the corresponding single-task score, proportional drop in performance under dual-task conditions relative to single task performance; absolute differences between single- and dual-task performance). Of the eight possible correlations between verbal and visual dual-task cost scores, virtually all correlations were non-significant. The authors concluded that their data provide no support for domain-general RI processes. Finally, Sulpizio et al. (2022) examined verbal semantic RI capacity via a lexical decision task (i.e., word and nonword strings have to be categorized regarding their lexical status, with the words being either neutral words or taboo words, the latter interfering with the lexical decision response) and a semantic Stroop task (i.e., written color-associated words, such as lawn/strawberry/sky/lemon, are presented in a congruent or an incongruent font) and visual RI via a Simon task (i.e., participants are presented with two horizontally aligned colored squares and are asked to categorized them based on their colors; half of the time the color response button is located on the same side as the stimulus and half of the times it is located in the opposite position). The authors observed a small-to-moderate size correlation (*r* = .25) between the verbal RI measures for the lexical decision and the Stroop task, but a non-significant correlation (*r* = values not reported) between RI measures for the Simon and the lexical tasks, as well as between the Stroop and the Simon tasks. These results also support the existence of domain-specific rather than domain-general RI processes.

We should note here that there is a much larger number of studies that have examined the occurrence of between-domain RI effects by comparing the occurrence of dual-task costs for same-domain and between-domain tasks or for same modality and between-response modality tasks, or by comparing the occurrence of phonological versus semantic interference effects (Araneda et al., 2015; Cowan & Barron, 1987; Cowan & Morey, 2007; Donohue et al., 2013; Driver & Baylis, 1993; Elliott et al., 1998, 2014; Guerreiro et al., 2013b; Hanauer & Brooks, 2005; Hazeltine & Wifall, 2011; Hirst et al., 2019; Ikeda et al., 2010; Miles et al., 1989; Redding & Gerjets, 1977; Roelofs, 2005; Tipper et al., 1988). However, for the reasons already specified, we did not include these studies in this review as they do not directly compare interindividual differences in RI capacity across domains. Note that for this section, no study comparing RI for phonological vs. semantic subdomains and corresponding to our search criteria was identified.

Neuropsychological data

RI for verbal vs. visual information in brain-damaged patients

Next, we examine neuropsychological studies that have compared RI abilities between domains, by focusing first on visual vs. verbal domains. These studies mainly involve patients with (a history of) aphasia and associated verbal working memory and control deficits.

Hamilton and Martin (2005) reported the profile of patient ML with a major left frontal lesion (i.e., left frontal and parietal operculum, with atrophy noted in the left temporal operculum and with mild diffuse atrophy) who showed impaired performance for the interference condition of the verbal Stroop task but not for a closely visuo-spatial variant of the Stroop task or for an antisaccade task (see Table 2 for a description of the tasks). In this patient, verbal and visual RI appeared to show a clear between-domain dissociation, even for closely matched RI tasks such as the Stroop task, and despite patient M.L. having no major naming difficulties (Martin & He, 2004; Martin & Lesch, 1996). More recently, Kuzmina and Weekes (2017) investigated RI in verbal and visual domains in a group of 31 patients with aphasia and healthy controls. Participants were administered a visual Flanker task (see Table 2), a cognitive control task (a rule finding task where participants were presented colored dots changing position and had to guess where the next one would appear), a verbal Stroop task for measuring RI, and an auditory-verbal control task (participants had to detect target stimuli within an auditory sequence while ignoring distractors semantically related to the distractor). Overall, the patients were less accurate in the Stroop task (fluent subgroup: $z = -2.32$; non-fluent subgroup: $z = -2.58$) and in the auditory-verbal control task (fluent subgroup: $z = -2.7$; non-fluent: $z = -4.10$) whereas in the general cognitive control task, only the non-fluent subgroup performed worse than controls ($z = -2.02$). Overall, the patients with aphasia showed stronger impairment in the verbal RI tasks compared to the nonverbal tasks, at least for the fluent subgroup.

In sum, the few studies presented here appear to support a dissociation of verbal versus visual RI abilities in brain injured patients. However, the extent to which these results reflect a more general dissociation between verbal vs. visual impairment remains a partially open question given that all dissociations are one-way, with impairment of verbal RI but preservation of visual RI abilities, in patients with associated language impairment.

RI for phonological vs. semantic information in brain-damaged patients

Next, we turn to the neuropsychological studies that have investigated dissociations between RI for phonological vs semantic domains within the verbal domain. These studies also mainly involve patients with aphasia.

Martin and Lesch (1996) presented the language and working memory profiles of three left-hemisphere damaged patients, the patients AB, ML and MS. Patients AB and ML were considered to have greater difficulties for maintaining semantic information in verbal tasks (as evidenced for example by more pronounced difficulties for word than nonword stimuli), a deficit that was subsequently interpreted as reflecting a deficit in resisting semantic interference. Indeed, these patients showed a significant proportion of intrusion errors in WM recall tasks, involving the production of words belonging to previous trials. This type of errors is uncommon for patients with a short-term maintenance deficit, as these patients will generally show increased forgetting instead of presenting increased recall rates for previously presented word. This pattern of results has been interpreted as an overactivation of semantic information and a difficulty of RI stemming from this semantic overactivation (Freedman & Martin, 2001; R. C. Martin & He, 2004). Patient M.S., who was instead supposed to present a decay-based, phonological WM impairment indeed did not show increased rates of intrusion errors involving items from earlier trials. This interpretation has been subsequently refined by paradigms designed to measure RI for semantic and phonological information more directly. One of these paradigms is the recent negative task in which lists of words are presented, each list being followed by a probe word for short-term probe recognition (Hamilton & Martin, 2005). Negative probe words are phonologically or semantically related to a word of either the current or a previous memory list. Here, no dissociation between phonological and semantic RI was observed, patient ML, supposed to have a specific semantic RI deficit, being generally slower in both conditions compared to the control group. On the other hand, Barde et al. (2010) demonstrated a distinction between phonological and semantic RI by administering the same type of recent negative task to 20 aphasic patients with left hemisphere lesions and phonological or semantic working-memory (WM) deficits. They showed that patients with a phonological WM deficit showed a stronger RI deficit for phonological negative probes in the recent negative task while patients with a semantic WM deficit showed a stronger deficit for semantic negative probes. More specifically, via stepwise regressions, they observed that a phonological composite WM score explained between 19% and 33% of the phonological interference score; a semantic WM composite explained between 2% and 29% of the semantic interference score. Each time, adding the other WM composite score to the regression did not increase predictive power. At the same time, these dissociations cannot be interpreted in an unambiguous manner given that the greater difficult to reject phonological/semantic distractors could stem from the reduced precision of phonological/semantic representations in WM given the associated, domain-specific WM impairment.

More recently, McCall et al. (2022) investigated phonological and semantic control in 32 aphasic patients with left hemisphere lesions via a switching-control task. Participants had to switch between the selection of 2 or 3 targets that are unrelated or phonological/semantic related, or just select 1 target. Here, interference was calculated by subtracting transformed time per target selection in the unrelated condition from transformed time per target selection in the phonological/semantic related condition. The authors observed impaired performance for the phonological interference condition ($d = 0.59$), but not for the semantic interference condition ($d = 0.23$)[2]. Correlations between the semantic and phonological interference measures were not significant (sequence length 1: $r = .30$; sequence length 2: $r = .34$; sequence length 3: $r = .25$).

Finally, Schnur et al. (2006) used a paradigm involving the progressive build-up of semantic interference, the cyclic naming task. In this task, semantic interference is instaured by having participants repeatedly name the same pictures involving objects from the same or a different semantic category (see Table 1). For same category objects, semantic representations will be progressively over-activated, leading to interference during naming as reflected by increased naming latencies for same-category relative to different-category objects over the different naming cycles. These semantic interference effects have been shown to be increased in patients with aphasia, and this particularly for patients with prefrontal lesions (Biegler et al., 2008; Damian et al., 2001; Jefferies et al., 2007a; T. T. Schnur et al., 2006, 2009b; Thompson et al., 2017). While phonological variants of this paradigm (the pictures to be named refer to phonologically similar names) have also been developed and shown to lead to increased interference effects in patients with aphasia (Hodgson et al., 2005), there are no direct comparisons so far between phonological and semantic interference build-up conditions of this task.

In sum, selective RI deficits for phonological vs. semantic information have been reported, but these dissociations are not systematic and could reflect, at least partly, domain-specific WM impairment rather than domain-specific RI impairment.

Neuroimaging studies

In this final section, we examine the neuroimaging studies that have examined the neural substrates of RI for visual vs. verbal domains, including the distinction between phonological and semantic verbal domains. We will first focus

2 Effect size estimated based on test statistics provided in the manuscript (Lenhard, W. & Lenhard, A. (2016). Computation of effect sizes. Retrieved from: https://www.psychometrica.de/effect_size.html. Psychometrica. DOI: 10.13140/RG.2.2.17823.92329)

on neuroimaging studies that have examined visual RI and verbal RI separately. We will then review the few studies that have directly contrasted visual and verbal RI.

The functional neural substrates of visual and verbal RI

One of the first studies focusing more specifically on RI in the visual domain is a study by Wager et al. (2005). The authors explored the neural substrates associated with RI in a Flanker task (see Table 1), a go/no-go task and a stimulus-response compatibility task (see Table1). Note however that both tasks also have a strong response inhibition component. The authors observed the recruitment of a large bilateral network involving, among other areas, the pars opercularis of the bilateral inferior frontal gyrus (IFG) when resisting to irrelevant visual stimuli. These findings are also in line with a study by McNab et al. (2008) which furthermore aimed at separating RI and working memory/attentional control components among three executive tasks (Go/No-Go, Flanker and a stop task) and two working-memory tasks (one spatial, one verbal). Using conjunction analyses over condition-specific univariate neural activity peaks, the authors observed that the right IFG as supporting more specifically the RI component while parietal cortices were associated with the working memory/attentional control components. In a further fMRI study, increased activity of the medial frontal and precentral gyri and decrease of the right IFG activity were observed during a Flanker task (see Table 1) (Zhu et al., 2010). A meta-analysis by Simmonds et al. (2008) on the visual Go/Go-No task identified the right middle/inferior frontal gyri as well as the bilateral inferior parietal and occipital regions to be specifically associated with the suppression of irrelevant, interfering visual stimuli. Another neuroimaging meta-analysis conducted by Nee et al. (2007) confirmed the implication of the right IFG/dorsolateral prefrontal cortex when interference resolution on visual information is involved. More recently, Weeks et al. (2020) investigated neural representations underlying visual RI by comparing responses to target and non-target stimuli during the delay phase of a WM task in young and older adults. They manipulated face, object, body, and scene stimuli. They observed recruitment of bilateral occipital and medial temporal cortices associated with visual processing. They also observed a higher activation in the right IFG when non-target stimuli occurred and had to be suppressed. However, one limit of this study, in the context of this review, is that the visual material (faces, objects, bodies, scenes) could be easily verbalized.

Table 2
Summary Table of Neuroimaging Studies of RI in the Visual Domain.

Studies	Regions	Tasks
Wager et al. (2005)	bilateral anterior insula/frontal operculum and anterior prefrontal, right DLPFC and premotor, and parietal cortices	Go/No-Go (letters), Flanker task (colors) and a stimulus–response compatibility (arrows) task
Nee et al. (2007)	right DLPFC right DLPFC, right IFG, insula	Flanker task Go/No-Go
McNab et al. (2008)	right IFG	Go/No-Go (squares), Flanker task (arrows) and Stop task (arrows)
Simmonds et al. (2008)	superior medial wall, right prefrontal regions, left premotor cortex, bilateral inferior parietal regions, bilateral occipital regions, bilateral putamen and insula	Meta-analysis on Go/No-Go brain activation
Zhu et al. (2010)	right IFG, MFG, PCG left MFG, PCG	Flanker task (arrows)
Weeks et al. (2020)	right IFG pars triangularis, right MTL, bilateral visual areas	Retrocue recognition task (faces, objects, bodies, and scenes)

Notes. DLPFC = dorsolateral prefrontal cortex, IFG = inferior frontal gyrus, MFG = medial frontal gyrus, MPFC = medial prefrontal cortex, PCG = precentral gyrus, MTL = medial temporal lobe, SGF = superior frontal gyrus.

Regarding verbal RI, one of the first studies that was conducted is a study by Petersen et al. (1999), which actually was one of the first neuroimaging studies on RI more generally. The authors examined the neural substrates associated with the verbal Stroop task (see Table 1) and observed increased activity peaks in the bilateral inferior frontal gyri (IFG) as well as in the anterior cingulate for the RI and response selection stages of this task. A number of subsequent studies have replicated this finding, and this mainly for the left IFG (Gruber et al., 2002; Manard et al., 2017; Parris et al., 2019; Peterson et al., 2002; Taylor et al., 1997; van Veen & Carter, 2005) (see Table 3). Other studies examined the neural substrates associated with the Picture-Word Interference task (i.e., naming pictures as quickly and accurately as possible while ignoring superimposed words; see Table 1). These studies also highlighted the involvement of the bilateral IFG (i.e., orbitomedial prefrontal cortex), together with the left mid middle temporal gyrus, left posterior superior temporal gyrus, and left anterior cingulate cortex (S. Abel et al., 2009, 2012; de Zubicaray et al., 2001; Gauvin et al., 2021).

In sum, the different studies reviewed here seem to converge on the involvement of the right IFG in visual RI and the left or the bilateral IFG in verbal RI (see also Figure 1 and Table 3). Other neural regions may also be involved in RI depending on the task used but it is unclear to what extent these regions are associated specifically to RI or to more specific verbal and visual processes.

Table 3

Summary table of neuroimaging studies of RI in the verbal domain

Studies	Regions	Tasks
Paulesu et al. (1997)	anterior triangular portion of the left IFG and the left thalamus	Phonemic fluency task
	posterior opercular portion of the left IFG for phonemic fluency left retrosplenial region of the left IFG for semantic fluency	Semantic fluency task
Taylor et al. (1997)	left IFG	Stroop task
Peterson et al. (1999)	bilateral IFG, anterior cingulate	Stroop task
Leung et al. (2000)	anterior cingulate, insula, premotor and IFG	Stroop task
de Zubicaray et al. (2001)	semantic: left mid middle temporal gyrus, left posterior superior temporal gyrus, left anterior cingulate cortex, bilateral orbitomedial prefrontal cortex	Picture-Word Interference Paradigm
Gruber et al. (2002)	anterior cingulate	Stroop task
Peterson et al. (2002)	anterior cingulate, supplementary motor, visual association, inferior temporal, inferior parietal, inferior frontal, and dorsolateral prefrontal cortices sand the caudate nuclei	Simon and Stroop tasks
McDermott et al.	semantic: left anterior/ventral IFG,	Blocked-cyclic

(2003)	approximate, BA47), left posterior/dorsal IFG (BA44/45), left superior/middle temporal cortex (BA22/21), left fusiform gyrus (BA37), and right cerebellum. phonological: left IFG (near BA6/44, posterior to the semantic regions within IFG described) and within bilateral inferior parietal cortex (BA40) and precuneus (BA7)	naming paradigm
van Veen & Carter (2005)	anterior cingulate, prefrontal, and parietal brain regions	Stroop task
Snyder et al. (2007)	phonological inhibitory control for words only: IFG phonological inhibitory control for nonwords: precuneus and supramarginal areas	Similarity-judgment and matching tasks with high and low conflict levels
Abel et al. (2009))	semantic: left orbitofrontal gyrus, left medial middle temporal gyrus, left angular gyrus phonological: left supramarginal gyrus	Picture-Word Interference Paradigm
Abel et al. (2012)	semantic: left middle temporal gyrus, left superior and inferior parietal lobule, and left inferior/middle FG phonological: right middle temporal gyrus, left precuneus, left inferior parietal lobule, left middle temporal and frontal gyri	Picture-Word Interference Paradigm
Manard et al. (2017)	bilaterally in the inferior frontal operculum and insula, and in the left precentral, inferior parietal and superior occipital gyri	Stroop task
Parris et al. (2019)	semantic: left IFG, right mediodorsal thalamus	Stroop task
Klaus & Hartwigsen, (2019)	semantic: anterior left IFG phonological: posterior left IFG	Category member vs. rhyme generation task
Attout et al. (2022)	semantic: bilateral angular gyrus, bilateral middle temporal gyrus and bilateral pars opercularis, orbitalis and triangularis	Similarity-judgment task

	phonological: pars triangularis of the bilateral inferior frontal gyrus and to the left middle temporal gyrus.

Notes. IFG = Inferior frontal gyrus

Direct comparison of neural substrates involved in verbal versus visual RI.

Next, we focus on studies that have directly contrasted RI in verbal and visuo(-spatial) tasks (see Table 4). Morimoto et al. (2008) presented two different versions of the Flanker task (Table 2): either a target color word that was flanked by a colored patch (visual RI) or a target-colored patch that was flanked by a color word (verbal RI). The left IFG showed higher activity levels in the verbal RI condition while the right IFG showed higher activity levels in the visual RI condition. These results echo the studies reviewed in the previous sections, indicating a possible left/right hemisphere distinction for verbal vs. visual RI. Schumacher et al. (2011) compared performance for visual and verbal/auditory versions of the Flanker task. Participants were presented two auditory or visual letters (A, B, C or D) and had to respond to the identity of the second letter while ignoring the first. They had to press a right key for A or B, and a left key for C or D. Interference was manipulated by presenting congruent trials involving the same response button for the two successive letters (e.g., B and A) or incongruent trials involving two different response buttons (e.g., B and D). At the behavioral level, the same congruency effect was observed (Eriksen & Eriksen, 1974) for auditory and visual modalities, meaning that the participants were generally slower to perform the incongruent trials rather than the congruent trials. At the neuroimaging level, the authors observed that verbal RI was associated with the left IFG while visual RI was associated with medial prefrontal, occipital and parietal areas as well as the putamen and the thalamus (see Table 4). Some areas were also associated with both verbal and visual RI: the bilateral precentral gyri and left superior frontal gyrus, the supramarginal gyrus, the supplementary motor area, and the putamen. However, the results of this study need to be considered with caution regarding the verbal vs. visual RI contrast given that the visual condition was merely the visual presentation of verbal presentation (letters).

Finally, Stephan et al. (2003) compared RI in verbal and visual domains by contrasting letter and visuospatial decision conditions. Participants were presented words composed of 4 letters, in which the second or the third letter was printed in red font. In the letter decision condition, verbal RI was manipulated by asking participants to ignore the position of the red letter and to indicate whether the word contained the target letter "A". In the visuospatial decision task, visual RI was manipulated by asking participants to ignore the language-related properties of the words and to judge whether the red letter was located at left or right relative to the center of the word. The authors observed that verbal RI was associated with the left IFG and anterior cingulate cortex while visual RI was associated with the right anterior cingulate and parietal cortices.

In sum, the studies directly comparing verbal and visual RI consistently highlight a specific involvement of the left IFG for verbal RI, and, but less consistently, a specific involvement of the right IFG in visual RI.

Table 4
Summary table neuroimaging studies directly comparing RI in visual and verbal domains.

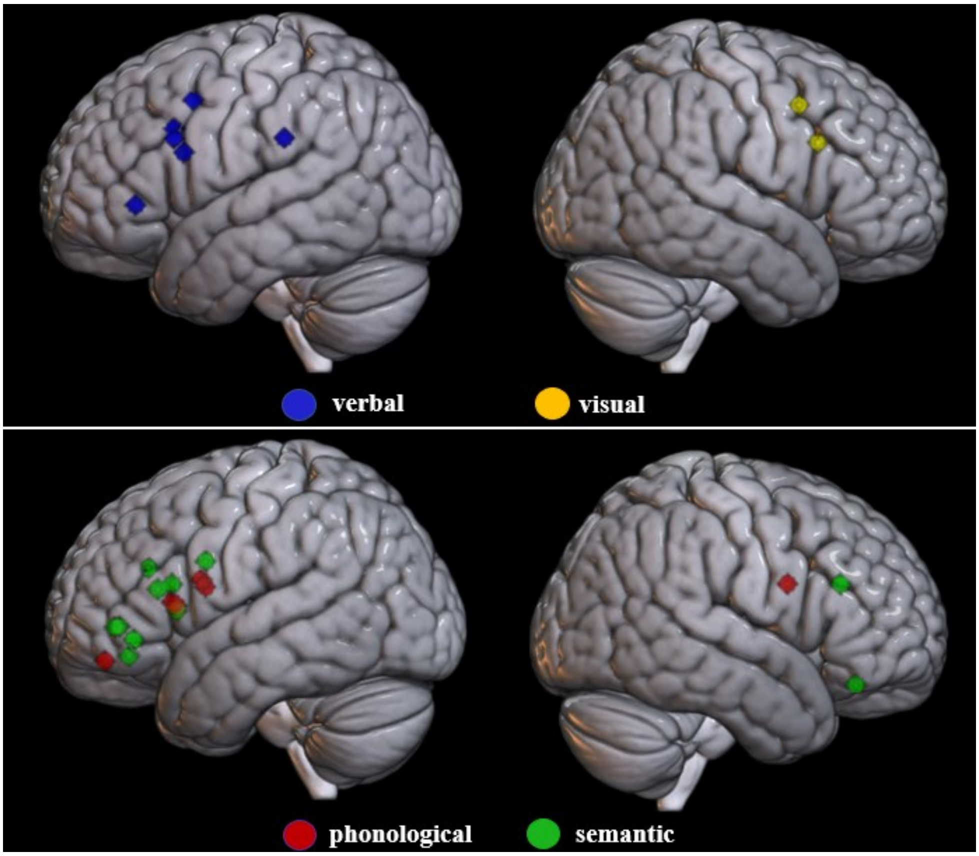
Studies	Underlying regions & neural mechanisms		Tasks
	Verbal	Visual	
Stephan et al. (2003)	left anterior cingular cortex, left IFG, fusiform gyrus, lateral extrastriate cortex, ventral premotor cortex and posterior IFG, supplementary motor cortex, bilateral primary visual cortex	anterior and posterior right inferior parietal lobule	Letter and visuospatial decision tasks
Morimoto et al. (2008)	left frontal inferior cortex	right frontal inferior cortex	Flanker tasks
Schumacher et al. (2011)	left inferior frontal gyrus	cingulate gyrus, left precentral gyrus, SMA, inferior temporal gyri, left post central gyrus, fusiform gyri, left superior and inferior	Flanker tasks

		parietal lobule, left and right middle and inferior occipital gyrus, left superior occipital gyrus, cerebellum, left putamen and thalamus
	both: bilateral precentral gyri and left superior frontal gyrus, supramarginal gyrus, supplementary motor area, and putamen	

Notes. IFG = Inferior frontal gyrus, SMA = supplementary motor area

Figure 1

Summary of the activity peaks observed in the left and right frontal lobes for between-domain contrasts of RI.



Notes. This figure was built by extracting first the MNI coordinates associated with contrasts between verbal semantic, verbal phonological and/or visual RI from the studies reported in this review. The selected MNI coordinates were then assembled using the WFU Pick Atlas (Maldjian et al., 2003, 2004) for each domain and displayed with a sphere shape of 5mm radius. These WFU-generated masks were then overlaid on a 3D render MRI template using MRICroGL (http://www.nitrc.org).

Direct comparison of neural substrates involved in phonological versus semantic RI.

Finally, we turn to studies that have directly compared RI for phonological vs. semantic information within the verbal domain. Paulesu et al. (1997) contrasted phonemic and semantic (category) fluency tasks. Although fluency tasks are multi-determined cognitive control tasks, they also involve a RI component given that already produced items interfere with subsequent item retrievals and need to be inhibited. The authors observed increased activity levels in the pars triangularis of the IFG for both tasks, but higher activity in the pars opercularis of the left IFG for the phonological task and higher activity of the left retrosplenial cortex for the semantic task. Other studies claimed that the anterior part of the left IFG would support RI and associated cognitive control in semantic tasks while the posterior part would support RI in phonological tasks (Klaus & Hartwigsen, 2019; McDermott et al., 2003). However, Snyder et al. (2007) investigated resistance to semantic and phonological interference using similarity-judgment and matching tasks with high and low conflict levels (see Table 1 for example). The authors observed no significant differences in neural responses in the left IFG between phonological and semantic conditions while showing at the same time generally enhanced activity levels in the left IFG in the high-conflict conditions. Using a similarity-judgment-task (see Table 1) and contrasting also high and low conflict conditions, Attout et al. (2022) recently compared semantic and phonological RI using both univariate and multivariate neuroimaging methods. The authors observed common involvement of the pars triangularis of the bilateral IFG and as well as the left middle temporal gyrus for both phonological and semantic RI, with further more widespread fronto-parietal involvement for semantic RI (see Table 2). Critically, multivariate neural patterns associated with phonological RI in different IFG areas could not predict neural patterns associated with semantic RI in the same areas, and vice-versa. These data indicate that even if similar neural regions may support both phonological and semantic RI, the neural processes involved differ. Finally, studies focusing on the picture-word interference task (see Table 1) also showed an involvement of the left

IFG as well as of temporo-parietal cortices in verbal RI (S. Abel et al., 2009, 2012). Importantly, differences were also observed for phonological versus semantic distractors, with phonological RI being associated with the left supramarginal gyrus and semantic RI with the left orbitofrontal gyrus, left medial middle temporal gyrus and left angular gyrus.

In sum, the neuroimaging studies reviewed here show that the left IFG, supports both phonological and semantic RI, with no clear distinction between anterior and posterior parts for the IFG (see Figure 1). But at the same time, there is also consistent evidence for a neural separation of phonological and semantic RI, semantic RI involving also more posterior temporo-occipital and temporo-parietal cortices. Most importantly, even if the same left IFG regions appear to be involved in both phonological and semantic RI, the specific neural processes supported by these regions appear to differ.

Discussion and Conclusion

This focused minireview examined behavioral, neuropsychological, and neuroimaging evidence for and against domain-general RI processes. Behavioral studies highlighted overall low associations between RI capacity across visual, verbal phonological and verbal semantic domains. Neuropsychological studies mainly showed dissociations for RI abilities between the three domains. Neuroimaging studies highlighted a left vs. right hemisphere distinction for verbal vs. visual RI, with furthermore distinct neural processes supporting phonological versus semantic RI in the left IFG. Overall, the results appear to support the view of domain-specific rather than domain-general processes. Noteworthy, even if evidence tends to support distinct RI mechanisms, it does not exclude the possible existence of additional, higher level and domain-general control processes over the different domain-specific RI mechanisms (as discussed below). Indeed, there are a number of methodological caveats that need to be discussed and that do not allow to disconfirm the hypothesis of additional, domain-general RI processes.

A first limitation is the small number of studies that have directly addressed the question of domain-specific and/or domain-general RI processes, particularly for behavioral and neuropsychological study designs. At the behavioral level, the vast majority of studies has tried to determine whether there are cross-domain interference effects when using dual task designs, and whether these effects are stronger of not for dual tasks from different versus the same domain. As already noted, this type of studies will inform us about the potential for interference between stimuli/tasks from different domains but not necessarily about the domain-specific and/or domain-general nature of RI processes. For example, strong between-domain dual task costs may reflect increased domain-general attentional control and division demands rather than evidence for domain RI processes. Studies correlating RI measures derived from separate tasks will be more informative as they will allow to directly compare RI ability across domains without the confound of additional executive costs associated with dual tasks. These correlational studies in healthy adults are however rare. At the neuropsychological level, most studies having compared RI across domains are single case studies, revealing only unidirectional dissociations (impaired verbal RI, preserved visual RI). Stronger evidence associated with double dissociations is still lacking and the more general verbal or working memory impairment shown by the patients could also have contributed to the simple dissociations that were observed.

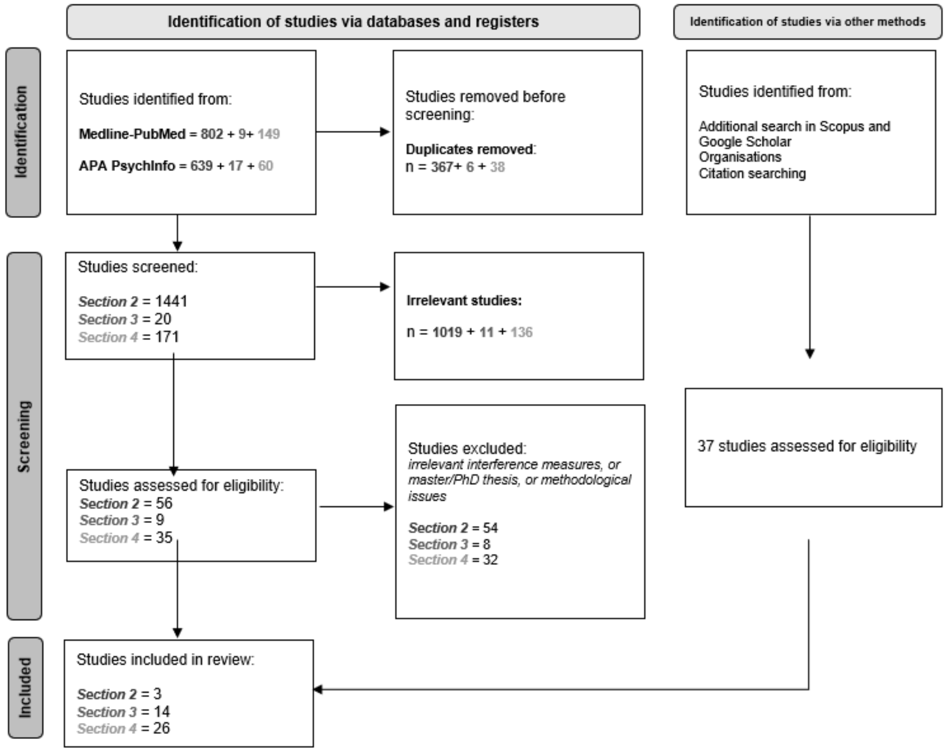
A second cautionary note needs to be raised regarding the comparability of tasks administered for assessing the RI across different domains. While many reported studies used tasks that were very closely matched across domains, with tasks having the same structure and only the nature of the stimuli being changed (e.g., recent negative task using either phonological or semantic probes, Hamilton & Martin, 2005; flanker task with written words vs. coloured patches, Morimoto et al., 2008; similarity-judgment task for words vs nonwords, Attout et al., 2022), this was not always the case (e.g., verbal Stroop task vs. visual Flanker task, Kuzima & Weekes, 2007). Tasks may differ in several other aspects associated with RI, such as the ease of prediction, selection and/or suppression of responses. Hence, we cannot rule out the possibility that the result of lack of association for cross-domain RI comparisons reported in some of the reviewed studies could have been inflated by structural task differences. At the same time, note that cross-domain RI dissociations were also observed in studies that used closely matched task designs. We should however mention here that the use of structurally equivalent tasks across domains does not necessarily guarantee that the amount of interference build-up is exactly the same in the different versions of the task. For example, while Attout et al. (2022) used very strictly matched task designs for probing phonological and semantic RI, by inducing the pre-activation of a phonological or a semantic representation that will interfere with the target response, it will be difficult to determine whether the pre-activations were exactly of the same strength within each domain and interfered to the same extent with the targets. For instance, while Attout et al. (2022) observed significant behavioral interference effects for both the phonological and semantic variants of the task, they also observed an interaction with slightly stronger interference effects in the semantic task. In contrast, other design choices could have biased results in favor of an absence of domain-specific RI, specifically when using words for probing both phonological and semantic RI (Hamilton & Martin, 2005, 2007a; R. C. Martin & Lesch, 1996). Word stimuli may incidentally elicit semantic/phonological processes even when the task focuses on phonological/semantic judgments or when no explicit processing of the word stimuli is required. Jedidi et al. (2021) showed robust involvement of semantic processing areas in temporal cortices during word presentation even when attention was absorbed by a primary visual search task; critically, they even observed the involvement of inferior frontal and mid-temporal areas associated with semantic control and inhibitory processes during incidental, passive processing of word stimuli.

Overall, despite the methodological caveats, the different studies reviewed here appear to favour the existence of domain-specific RI processes rather than purely domain-general RI processes. This does however not mean that RI processes arise exclusively from processes embedded in domain-specific representational systems. This review does not discard the possibility of the co-existence of domain-specific and domain-general, or at the least, central RI control processes, as explicitly or implicitly assumed by some models of cognitive control (Verbeke & Verguts, 2021; Verguts, 2017). The neuroimaging data reviewed here are of particular interest as they suggest, on the one hand, a general implication of prefrontal cortices in RI across domains, but at the same time a specialization of prefrontal cortices for RI as a function of visual vs. phonological vs. semantic stimulus domain. It could be assumed that prefrontal cortices are a central controller of RI by keeping track of task-relevant information, but this can only work in synergy with information-specific representational domains in which task-relevant information is processed. Verbeke and Verguts (2021) proposed a computational model assuming that the synchronization of neural oscillations between prefrontal control systems and posterior domain-specific representational domains allows privileged processing of target vs. non-target information, a situation equivalent to RI (Verbeke & Verguts, 2021). These predictions resonate with the findings of Attout et al. (2022) showing that the same prefrontal regions can be involved in RI for phonological and semantic information, but that they represent different information according to phonological vs. semantic RI situations. By transposing these results to the model by Verbeke and Verguts, it could be argued that the neural state of the prefrontal controller will necessarily differ depending on the type of target information it needs to keep track and type of representational neural network it needs to interact with. Dissociations of RI between verbal and visual domains could occur due to differences in neural connectivity and synchronization between prefrontal control and specific posterior representational systems.

To conclude, the studies reviewed here support a domain-specific rather than a domain-general view of RI processes. However, evidence is still fragmentary and does not allow to rule out domain-general RI processes. Recent computational models of cognitive control are compatible with a hybrid view in which domain-general RI mechanisms can materialize as domain-specific abilities due to the interaction between domain-general RI mechanisms and domain-specific representational systems. But in that case, evidence for the domain-general RI mechanisms should also be observable because a general weakness of the domain-general controller should lead to similar RI impairment across domains. Furthermore, it is important to note that RI is a complex cognitive capacity that likely involves multiple mechanisms and processes, some of which are domain-specific, without excluding the existence of additional domain-general RI control processes. Future studies, comparing RI for different stimulus domains but with structurally and functionally equivalent tasks, are necessary to further elucidate the complex question of domain-general and/or domain-specific RI processes.

Appendix

Number of Articles Returned at Every Step of the Research Strategy.



Note. also available on https://osf.io/wbk8f/ .

A database distinguishing concreteness, imageability and emotional valence values for nouns and verbs in French

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Abstract. Concreteness, imageability or emotional valence are known to determine performance in different psycholinguistic tasks. Yet, existing databases for these psycholinguistic parameters in the French language are limited and the difference between imageability and concreteness is often neglected. The present work extends existing database by providing imageability, concreteness and emotional valence values for 177 nouns and 165 verbs. Data were collected from 258 native French speakers from France and Belgium. We provide mean imageability, concreteness and emotional valence values, as well as inter-rater reliability values for each value and stimulus. The database is available on https://osf.io/453ft/.

Keywords: concreteness, imageability, emotional valence, norms, verbs

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Declarations of interest: The authors have no potential conflict of interest to declare.

Ethics: The study is in accordance with the ethical principles of the Declaration of Helsinki and the participants have signed a consent form.

Introduction

Psycholinguistic variables such as concreteness, imageability or emotional valence are known to influence processing of verbal stimuli in many different cognitive tasks (Rofes et al., 2018). Concreteness refers to the perceptual semantic dimension(s) associated with a word/concept[3], such as its associated visual, auditory, tactile, motor, olfactory or gustative features (Bonin et al., 2018). For example, “cat”, as opposed to “freedom”, is a highly concrete word as it refers to a concept associated with vivid sensory characteristics (visual: the color of the fur, the size and shape of the animal; auditory: the sounds it emits; tactile; what it feels like when we touch/caress a cat). Imageability is often considered to be a sub-dimension of concreteness referring to the ease with which a mental (often visual) image can be formed for a word/concept (Desrochers & Thompson, 2009; Thomas, 2004). Emotional valence refers to the emotional characteristics associated with a word/concept, which are often qualified as positive vs. negative emotional features, that is, their degree of pleasantness (Bonin et al., 2003; Bradley & Lang, 1999b, 1999a; Lang et al., 1997). Among these three variables, the existing French databases lack information about specific item categories, especially verbs, and ratings for the different variables lack uniformization in terms of type of rating scales. Therefore, the present study provides normative data for concreteness, imageability and emotional valence values for a selection of nouns and verbs.

Concreteness

In psychological studies, the processing of concrete words leads to faster response times or/and less errors as compared to abstract words (Bonin et al., 2018). Advantages for processing concrete words have been observed in many different cognitive domains such as declarative long-term memory (Paivio, 1971), oral and written language (Roxbury et al., 2014), working memory (van Schie et al., 2005; Walker & Hulme, 1999), language comprehension (for a review, see Fischer & Zwaan, 2008) and episodic memory (Jessen et al., 2000; Sadoski, 2009). For instance, responses to concrete words in lexical decision tasks are characterized by faster reaction times and higher accuracy compared to responses to abstract words (van Schie et al., 2005). This effect is stable across the developmental lifespan (Roxbury et al., 2016) and can be particularly marked in case of patients with

[3] It is also noteworthy to underline that in psycholinguistics, a word refers to a unit of language that carries meaning. In our example, "cat" is a word that refers to a specific type of animal – thus, when using the word “cat”, we directly refer to its referent.

acquired or progressive language impairment (Jefferies et al., 2007a; Sandberg & Kiran, 2014), with sometimes reversed concreteness effects in patients with a specific loss of perceptual semantic features such as in fluent primary progressive aphasia (semantic dementia) (Breedin et al., 1994; Jefferies et al., 2009).

Paivio (1971, 2010, 2013) explained the concreteness effect via a dual coding hypothesis. Concrete concepts would benefit from dual coding as they can be processed through both verbal and visual modalities. At the opposite, abstract concepts can be processed only through verbal coding. This account suggests that concreteness has an effect on cognitive processing because concrete concepts are more easily and vividly represented in the mind compared to abstract concepts. Later, the field of embodied and grounded cognition, proposed by Barsalou (1999, 2008) suggested that cognitive processes are fundamentally grounded in sensorimotor information. This theory posits that our conceptual understanding of the world is closely tied to our bodily experiences and interactions with the environment. The two frameworks are not exclusive and can be considered as complementary as Paivio's works emphasis that mental representation can take various forms, with some of these forms (i.e., mental image) relying on experience-based sensory representations.

Norms for the concreteness dimension have been provided in a relatively extensive manner for words of the English language, although the norms are often restricted to nouns (see for example Coltheart, 1981) (but see, for verbs, Klee & Legge, 1976; see also Palazova et al., 2013, for German verbs and Tsai et al., 2009, for Chinese verbs). In French, available concreteness ratings are limited to nouns (Bonin et al., 2003 and 2018, for 866 nouns and 1659 nouns, respectively).

Imageability

Like the concreteness effect, the imageability effect is characterized by faster and more accurate processing for words/concepts associated with high imageability values, and this across the same cognitive domains as the concreteness effect (oral and written language, (Coltheart et al., 1988; Ferrand et al., 2010; Majerus et al., 2002; working memory, Kowialiewski & Majerus, 2018, 2020; episodic memory, Burger et al., 2017). For example, higher immediate recall performance was observed for lists of high vs low imageability words in a verbal working memory paradigm by Kowialiewski and Majerus (2020). Because imageability and concreteness may give rise to quasi-perceptual experiences (Thomas, 2014), they are likely to influence cognitive functioning according to this field of research (memory embodiement: de Vega et al., 2021; Dutriaux et al., 2019; language functioning: Bidet-Ildei & Toussaint, 2015).

While imageability could be considered as a sub-dimension of the concreteness effect and explains an important part of this effect (Kousta et al., 2011; Reilly & Kean, 2007), it is important to distinguish both variables as words can be matched for imageability and yet differ for concreteness(for example, “bread” and “stone” may both be highly imageable but they will differ regarding other concrete dimensions such as olfactory, gustative and tactile features associated with the word). Concreteness is indeed often considered to refer to different sensory dimensions and, contrary to a frequent usage of the ‘imageability’ variable, is not restricted to the visual dimension (Brysbaert et al., 2014; Lynott & Connell, 2009; Paivio et al., 1968).

Some studies tried to dissociate imageability and concreteness dimensions in a more formal manner. Richardson (1976) used a latent variable approach to examine whether concreteness and imageability load on the same latent variable or if they represent two different constructs. He suggested that imageability and concreteness are theoretically and experimentally different constructs, despite their high correlation. More recently, Khanna and Cortese (2021), noted that imageability has a stronger effect on recognition memory task than concreteness. The authors used imageability, concreteness, perceptual strength, and action strength ratings to predict reading performance, recognition memory and lexical performances. They showed that imageability was the best predictor among the different investigated variables. As for concreteness, there are several important databases of imageability rating for the English language, both for noun and verb stimuli (Chiarello et al., 1999; Cortese & Fugett, 2004; Davies et al., 2016; Stadthagen-Gonzalez & Davis, 2006). In French, there are a number of databases for imageability ratings. Content et al. (1990) reported in their BRULEX database 1086 imageability values for nouns initially determined by Hogenraad and Orianne (1981). Bonin et al. (2011) collected imageability data for 1493 nouns, Ballot et al. (2022) for 1286 nouns and Desrochers and Thompson (2009) for 3600 nouns, each study using a 7-point scale. Recently, Ballot et al. (2022) provided imageability ratings for words from various grammatical categories (i.e., 50.5% nouns, 13.2% adjectives, 36.1% verbs, 0.2% adverbs). Only Bonin et al. (2003) reported values for both imageability and concreteness for 866 nouns, using a 5-point rating scale. However, verbs are also strongly affected by imageability processes, as a function of the extent to which verbs evoke sensory and perceptual experiences that can be easily imagined or more abstract actions. For example, the verb "to run" is more imageable than the verb "to think" because it evokes a more vivid and concrete sensory experience that can be easily imagined. Therefore, our aim was to complete and extend the available databases, especially with regards to verbs where the imageability dimension could be particularly determining (e.g., action verbs vs. other categories of verbs).

Emotional valence (EV)

Emotional valence, like concreteness and imageability, represents a semantic feature of a word/referent and provides information about its emotional polarity in this specific study. In general, words with strong positive or negative emotional valence can be considered to have a richer semantic representation compared to words with neutral emotional valence due to their added emotional semantic features. The effect of emotional valence of verbal stimuli on cognitive tasks is more complex than the effect of concreteness and imageability given that emotional valence does not only differ in polarity (positive-negative) but also in arousal (high-low; see also Note 1 in the Methodology section). Note that we limit our discussion here only on the immediate impact of the emotional valence of a word on a cognitive/psycholinguistic task, and we do not consider the situation of emotional induction where sets of emotional stimuli are used to manipulate the emotional mood of participants in an experiment. While both positive and negative valence can have an effect on processing words in oral and written language processing (Briesemeister et al., 2011), episodic memory (Comblain et al., 2004; D'Argembeau & Van der Linden, 2005; Kensinger & Corkin, 2003; R. C. Thomas, 2006) or working memory (Ferré, 2002; Lindström & Bohlin, 2011; Majerus & D'Argembeau, 2011), the directionality of this effect still remains poorly understood. Positive and negative words often lead to facilitated and more accurate processing, relative to neutral words, but no effect or a reversed effect have also been reported (Garrison & Schmeichel, 2019; Kensinger & Corkin, 2003; Majerus & D'Argembeau, 2011). For example, Majerus and D'Argembeau (2011) showed better memory recall performance for word lists with emotional content compared to word lists with neutral content, indicating a strong impact of emotional valence on pure list recall. However, when lists were mixed (i.e., neutral and positive/negative), the list with the least emotional items were best recalled. This is likely due to the additional interaction between emotional semantic features and attentional processes. Emotional stimuli are preferentially captured by the attentional focus, leading to facilitated or decreased performance depending on the amount of emotional stimuli to be processed and the nature of attentional control processes required by the specific task (see Majerus & D'Argembeau, 2011, for a theoretical discussion and model of the interactions between semantics, attentional control and working memory processes). Other authors have suggested that emotional effects may vary according to the categorical vs. continuous manner in which emotional valence is manipulated, and this more specifically in the context of lexical decision tasks (Briesemeister et al., 2011; Estes & Adelman, 2008; Larsen et al., 2008). In sum, emotional valence is associated with complex effects in cognitive tasks which are not yet fully understood and hence is an important variable to control.

Regarding databases focusing specifically on emotional valence (and not on other emotional dimensions such as arousal, type of emotion), a number of databases for word stimuli exist in different languages (see Hinojosa et al., 2016, for a recent synopsis). For the French language, we can cite the databases proposed by Bertels et al., 2009; Bonin et al., 2003; Gilet et al., 2012; Gobin et al., 2017; Monnier and Syssau, 2014; Syssau & Font, 2005; and Syssau & Monnier, 2009. These databases mainly focus on nouns and none of them controls for other associated dimensions such as imageability or concreteness. These variables can have shared effects as demonstrated by Ballot et al. (2022) in which emotional words were estimated as more imageable than neutral words or in Bonin et al. (2018) where emotional valence and concreteness were positively correlated.

The present study

This study aims at extending existing databases for concreteness, imageability and emotional valence[4] ratings of French words, by providing scores for the three dimensions at the same time and by including not only nouns but also verbs. Existing databases in French are particularly poor regarding ratings for these three dimensions for verb stimuli and/or do not consider all of these three dimensions at the same time. Imageability, concreteness and emotional valence ratings may be particularly relevant for verbs as one of the main function of verbs is to describe actions, actions being defined by rich sensory-motor experiences and associated emotional consequences (e.g., to punch vs. to caress). We report rating scores for 342 items including 165 verbs and 177 nouns, respectively representing 48.2% and 51.8 % of the material. All items were evaluated for emotional valence, concreteness and imageability, but by separate groups of raters so that the ratings for

[4] This study was conducted during the first year of the Covid-19 pandemic, potentially associated with a globally increased arousal level in participants that may have led to exaggerated estimations of arousal levels of specific words. Since the goal of this study was to collect generally representative, normative data, we chose not to ask participants to rate arousal levels associated with the items.

one dimension were not influence by the rating for the other dimension (Moors et al., 2013).

Method

Participants

We randomly recruited participants via social network platforms and university-based communication platforms to obtain a representative sample of the young adult general population. There was a total of 258 participants with 86 participants for the rating of each of the three dimensions. All participants were native French speakers from either Belgium (Concreteness: N = 44; Imageability: N=32; Emotional Valence: N=39) or France (Concreteness: N = 42; Imageability: N=52 + 2 both French & Belgian; Emotional Valence: N=47). Demographic information for each participant group is given in Table I. The ethical committee of the Faculty of Psychology, Speech and Language Pathology and Educational Sciences at the University of Liège had approved this study (file number 1779-46), following Helsinki declaration. A secure online questionnaire platform developed and hosted by our Faculty was used for data collection, and no other specific online software were used to retrieve participants responses. All participants electronically signed a consent form before starting the questionnaire and anonymized data were collected.

Table 1
Demographic Characteristics of the Participants

	Concreteness group	Imageability group	Emotional valence group
Mean age in years (standard deviation)	26 (11)	25 (7)	23 (7)
Sex	Men = 23 Women = 63	Men = 28 Women = 58	Men = 19 Women = 66 Other = 1
Mean number of years of education (standard deviation)	15 (2)	15 (3)	14 (2)

Material

The general psycholinguistic characteristics of the nouns and verbs (including pronominal and non-pronominal verb forms) selected are presented in Table II and in Appendix 2. These verbs were chosen from the PLAViMoP database of human action displays (Decatoire et al., 2019) and the nouns were chosen to match the verbs in terms of word length and lexical frequency range. The stimuli we selected stemmed from nouns and verbs already used in existing tasks (for the nouns, Attout et al., 2022; for the verbs, Villatte et al., 2022) and planned to be used in future studies. The verbs further corresponded to videos of actions stored in a free online database and frequently used as material in the studies by the authors - https://plavimop.prd.fr/index.php/en/.

Table 2.
General Psycholinguistic Characteristics of The Nouns and Verbs Selected for the Database

	N-Letters		N-Syllabes		Freq films	
	V	N	V	N	V	N
Mean	7,09	6,20	2,44	1,88	27,61	50,96
Std. Deviation	1,27	1,80	0,66	0,84	50,35	93,02
Minimum	4,00	3,00	1,00	1,00	0,01	0,20
Maximum	11,00	13,00	4,00	5,00	345,68	570,30

Note. V = verbs; N = nouns; N-Letters = Number of letters; N-Syllables = Number of syllables; Freq Films = frequency of the word according to the subtitle corpus (per million occurrences), from Lexique.org (New et al., 2001, 2004). 23 values are missing for the verbs as it corresponds to pronominal verbs.

Procedure

Each participant launched an online questionnaire from their own computer at a time of their choosing and could take part in only one questionnaire. The order of the words within the questionnaires was randomized between group of participants. Answers were given using 5-point assessment placed below each item to be assessed. The 5-point Likert scales were chosen to be consistent with previous studies (Alario & Ferrand, 1999; Bonin et al., 2003, 2018). Specific instructions and examples were given for each questionnaire (see Appendix 1 for the original instructions and their translation).

For the assessment of concreteness, participants were asked to rate the degree of concreteness of the items on a scale ranging from not concrete to very concrete, using a 5-point scale: 1 = not concrete; 2 = not very concrete; 3 = moderately concrete; 4 = somewhat concrete; 5 = strongly concrete. In order to guarantee a good understanding of the instructions, participants were provided the following instructions and examples*: Think for example of the word "cat". This word will probably seem very concrete to you quickly, so it will get a high concreteness score. On the other hand, the word "loyalty" will not seem very concrete and will get a low concreteness score. In the same way, the verb "to cook"* *designates an action that will undoubtedly seem concrete to you, whereas the verb "to think" will undoubtedly seem to designate a less concrete action*. In addition, to avoid any confusion, we also specified the participant to be careful and to make sure they rated the concreteness of the items: *Be careful, it is not about the image you have of the words, but about how well they represent a concrete concept.*

For the assessment of imageability, participants were asked to score the imageability dimension of the 342 items by using a 5-point scale ranging from 1 = not/very poorly imageable; 2 = poorly imageable; 3 = moderately imageable; 4 = well imageable; to 5 = strongly imageable. The following instructions/examples were provided: *Think of the word "cat" for example. You can probably form a mental image corresponding to this word in an easy and quick manner. The word cat will therefore get a high imageability score (5 = strongly imageable). On the other hand, you will find it probably be more difficult and time-consuming to form a mental image corresponding to the word "loyalty". Therefore, this word will get a low imageability score (1 = not/very poorly imageable). In the same way, the verb "to cook" refers to an action that you will probably find easy and quick to mentally visualize. Conversely, the verb "to think" will probably elicit an image only with some difficulty ".*

For the assessment of emotional valence, participants were asked to determine whether the items present were pleasant or not by using a 5-point scale ranging from 1 = very negative; 2 = somewhat negative; 3 = neutral; 4 = somewhat positive; to 5 = very positive. The following instructions/examples were provided: *Think about the word "charity". This word will probably sound very positive to you, and will get a score of "5, very positive". On the other hand, the word "table" might seem neutral and get a score of "3, neutral" while the word "betrayal" might get a score of "1, very negative". Similarly, a verb like "to offer" will probably sound very positive. Other verbs, such as "to sit down", might seem more neutral, whiles still other verbs, such as "to betray", might seem very negative.* Moreover, we also wanted to make sure that participants were rating emotional valence and no other dimensions, by adding: *It is not the image you have of these nouns and verbs you should assess, but the emotional value you attribute to them*.

As already noted, in the given examples, as well in all other examples mentioned in our manuscript, when we mention the label 'word', it refers to its referent. This was done to make the instructions simple and easy-to-follow for the participants. Making a distinction between a word and its referent in the instructions could have added unnecessary complexity.

For all three questionnaires, participants were instructed to evaluate the items by using the entire scale. Participants had the possibility to stop the questionnaire whenever they wanted but only full data sets were retained for analysis. The questionnaire started with the display of the general instructions along with the consent form, and demographic information were then collected on a second page. On the third page, detailed instructions and examples were displayed, followed by the stimuli to be assessed. Verbs and nouns were on different assessment blocks, organized vertically.

Results

Reliability and concurrent validity

Reliability was assessed with intraclass correlations coefficients with both participants and items as random factors (Shrout & Fleiss, 1979). To examine the validity of our ratings, we correlated the scores obtained with those of previous studies (for shared stimuli) using Spearman correlation tests. Intraclass correlations coefficients were calculated using JASP 0.16.0.0 for concreteness, imageability and emotional valence. These analyses confirmed high agreement (Koo & Li, 2016) between the 86 raters, with kappa = 0.97 for concreteness, kappa = .98 for imageability, and kappa = 0.98 for emotional valence. To examine the concurrent validity of our database, between-database Spearman correlations were conducted for mean concreteness, imageability or emotional valence ratings for stimuli shared with other databases which also used a 5-point rating scale. For concreteness, our database shared 77 words in common with Bonin et al. (2018) and 83 words in common with Bonin et al. (2003). Strong positive correlations were observed with Bonin et al. (2018) (r = 0.88) and Bonin et al. (2003) (r = 0.75). Concerning imageability, our database shared 83 words with Bonin et al. (2003), leading also to a strong positive correlation r = .78. For emotional valence, our database shared 96 items in common with Syssau and Font (2005), 83 in common with Bonin et al. (2003) and 77 in common with Bonin et al. (2018). Strong positive correlations were found with the three datasets (r = 0.89, r = 0.83 and r = 0.90, respectively). All these correlations are significant at p <0.001.

Ratings of the different variables

The database is freely accessible at https://osf.io/453ft/ as fully searchable .xls and .csv files. It contains the 342 French items in alphabetical order, as a function of grammatical class, together with their English translation as well as the means, standard deviations, and intra-class correlation coefficients, separately for concreteness, imageability and emotional valence values. For ease of use, we have also included already existing information about lexical frequency (freqfilm), number of letters and number of syllables, taken from Lexique 3.83 (New et al., 2001, 2004)

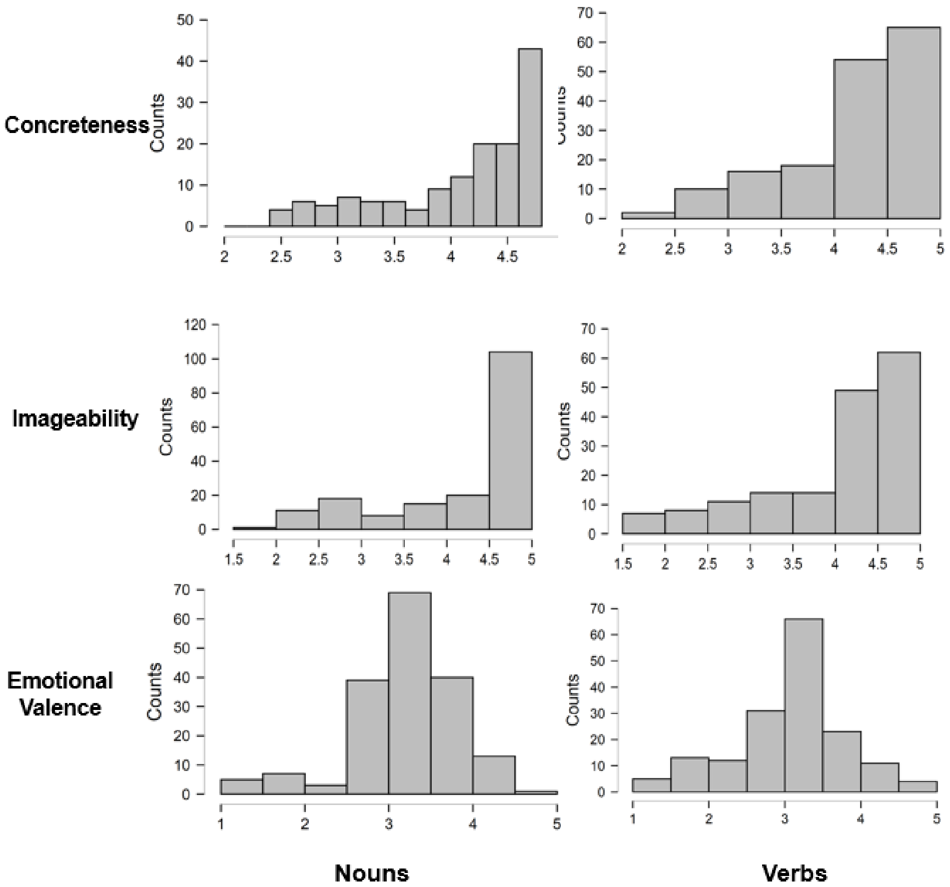
Descriptive statistics for the ratings of emotional valence, imageability and concreteness are presented in Table III. Figure 1 shows the distributions of the ratings. For concreteness and imageability values, distributions appeared to be skewed to the right and the kurtosis estimates were positive (i.e., a leptokurtic distribution), indicating an overrepresentation of highly concrete (similar to Bonin et al. 2003, 2018) and imageable items. Regarding emotional valence, the distribution appeared to be less skewed and to follow a mesokurtic normal distribution, indicating that most items were rated as neutral in line with Bonin et al. (2003) who also showed that emotional valence values were centered on the neutral mid-point.

Table 3
General Statistical Characteristics of the Imageability, Concreteness and Emotional Valence Ratings

	Imageability		Concreteness		Emotional Valence	
	V	N	V	N	V	N
N	165	177	165	177	165	177
Mean	4.014	4.205	4.171	4.244	3.095	3.205
Std. Deviation	0.859	0.867	0.643	0.675	0.724	0.615
Skewness	-1.177	-1.191	-1.205	-1.173	-0.332	-0.921
Kurtosis	0.293	0.105	0.535	0.203	0.314	1.897
Minimum	1.682	1.744	2.279	2.442	1.233	1.105
Maximum	4.906	4.976	4.953	4.907	4.860	4.547

Note. V = verbs; N = nouns.

Figure 1.
Distribution of the ratings for Concreteness, Imageability, and Emotional Valence



Correlations between variables

Next, we examined the interrelations between the three variables. Tables IV and V and Figure 2 show the Spearman correlations between mean imageability, concreteness and emotional valence values. A highly positive correlation was observed between imageability and concreteness rating for both verbs and nouns. These positive correlations are in line with previous studies (Paivio et al., 1968; Richardson, 1976). On the other hand, emotional valence ratings correlated only (very) weakly with the imageability dimension for verbs (p = .037).

Tableau 4
Correlations between Imageability, Concreteness and Emotional Valence for Verbs

Variable	Imageability	Concreteness	Emotional Valence
Imageability	—		
Concreteness	.91***	—	
Emotional Valence	.16*	.14	—

* p <.05, *** p < .001

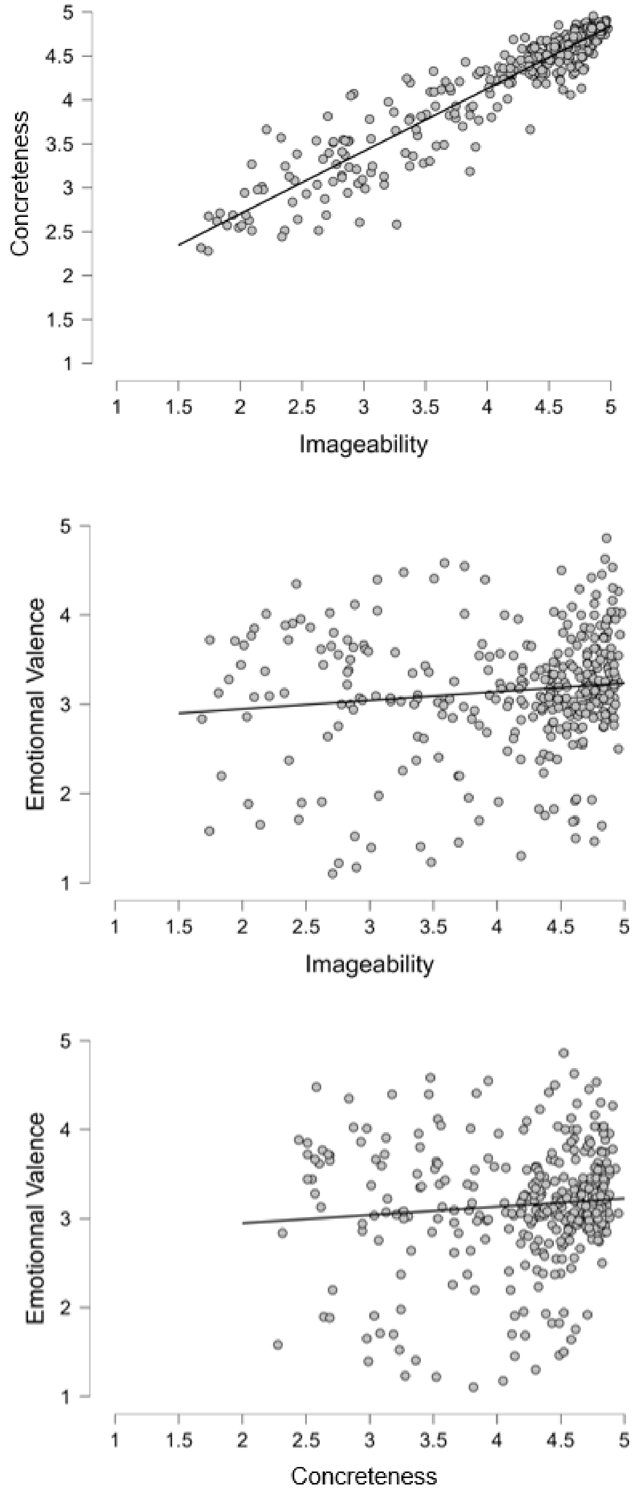
Table 5
Correlations between Imageability, Concreteness and Emotional Valence for Nouns

Variable	Imageability	Concreteness	Emotional Valence
Imageability	—		
Concreteness	.92 ***	—	
Emotional Valence	.12	.09	—

*** p < .001

Figure 2

Scatterplots for mean concreteness, imageability and emotional valence values



Discussion

We collected norms from 342 French nouns and verbs for concreteness, imageability and emotional valence variables from 258 young adult raters. All ratings were associated with high inter-rater reliability. Contrary to previous databases, our database is not limited to nouns but also includes verbs in various forms (including pronominal and non-pronominal verb forms). Finally, the ratings are based on a larger sample than most of the samples used in previous French studies when focusing on the number of participants who rated all the different items. For example, in Bonin et al. (2021), 31 participants completed one questionnaire/variable; in Bonin et al. (2018), there were between 25 to 33 participants per questionnaire; in Bonin et al. (2013), 30 participants rated the items; in Bonin et al. (2005), there were around 25 participants per item; in Gilet et al. (2012) there were between 19 to 22 participants per age group for each variable; there were 72 participants per questionnaire in Desrochers et Thompson (2009), and only one study (Syssau and Font, 2005) had each item judged by 100 participants. We should however acknowledge that these studies were able to assess more items overall (even if by different participants).

In accordance with previous studies (Bonin et al., 2003, 2018 for French norms), we observed a high positive correlation between concreteness and imageability, for both nouns and verbs. Both dimensions depend on the sensory experience associated with words, and such a strong correlation may thus not appear surprising. This also raises the questions of the separability of these two dimensions, which are, at the very least, strongly overlapping. Dellantonio et al. (2014) suggested that contrary to concreteness, imageability may rely on proprioceptive, interoceptive or affective states associated with the words. Imageability would engage both external (vision, audition) and internal perception (interoception) while concreteness would only be determined by external perception. A study on French stimuli collected norms by distinguishing between external and internal perceptual experiences elicited by a set of 270 words (Miceli et al., 2021). The study showed that the higher the interoceptive ratings, the smaller both concreteness and imageability ratings, disconfirming the proposal of Dellantonio et al. It should however be noted that the study by Miceli et al. included mostly concrete words, and hence a full assessment of the claim still needs to be undertaken. For this purpose, the inclusion of verbs could be highly informative. Verbs, and particularly action verbs, are not only defined by strong sensory-motor experiences but verb processing may be more self-centered than noun processing and associated with particularly pronounced interoceptive, aspects. Furthermore, presenting verbs in a first-person format (e.g., I play) versus a third person format (e.g., he/she plays) may further modulate interoceptive experiences elicited by verbs (Dellantonio et al., 2014). In the present study, there appears to be no difference between verbs and nouns in terms of concreteness, imageability, and emotional valence while other studies have shown nouns to be more imageable for verbs (Bird et al., 2000; Simonsen et al., 2013). Again, the role of pronominal versus non-pronominal verbs needs to be examined here. In French, verbs can endorse a reflexive form (e.g., "se lever", to get up), a reciprocal pronominal form (e.g, "s'embrasser", to kiss (each other)), an essential pronominal form (e.g., "s'évanouir", to faint) and even idiomatic pronominal form (e.g., "se dépêcher", to hurry up). We could hypothesize that a pronominal form involves the first-person point of view to a greater extent, leading to a stronger perceptual experience associated with a verb presented in its pronominal form, a hypothesis to be tested in future studies.

Regarding emotional valence, an interesting finding of the present study is that emotional valence ratings did not correlate with imageability or concreteness ratings, unlike the results of some previous studies (Bonin et al., 2003; Khanna & Cortese, 2021; Yee, 2017). One may argue that this situation mirrors the mixed impact of emotional valence overall on cognitive and psycholinguistic tasks (Delaney-Busch et al., 2016; Ferré et al., 2015). On the other hand, it should be noted that most of the material used in this study was associated with neutral emotional valence values, meaning that only very few words were associated with high emotional valence. This specific situation makes it difficult to draw any strong conclusions about the lack of association between emotional valence and concreteness/imageability ratings observed in the present study. We should note here that the exploration of this association was not the actual goal of our study, as our study simply aimed at providing a database of ratings about emotional valence and word imageability/concreteness for a set of nouns and verbs.

One limitation of this work is that we did not include arousal (i.e., activation or alertness that an individual experiences in response to stimuli or situations). For example, emotionally arousing words or sentences, such as those associated with fear or excitement, can elicit a heightened state of arousal compared to neutral words or sentences. This arousal level can affect how individuals process and interpret language. It would be particularly important to obtain additional normative data on this specific dimension for verbs given the scarcity of data for this specific word category. Moreover, perceptual features associated with words could be assessed in a deeper and more fine-grained manner via a 5-senses rating procedure (Chedid et al., 2019; Khanna & Cortese, 2021; Lynott & Connell, 2009; Miceli et al., 2021).

Finally, our normative data for these dimensions will complete the already existing French databases (see Bertels et al., 2009; Bonin et al., 2003, 2011, 2018, 2021; Desrochers & Thompson, 2009; Gilet et al., 2012 for different norms and variables) particularly for verb stimuli. Providing accurate and precise norms for language-specific stimuli is also important as languages may differ with respect to the semantic richness implied by specific words. Indeed, perceptual and sensorimotor features associated with a specific word rely on personal experience which can differ across different cultures (see, for example, Simonsen et al., 2013 on semantic specificities of the Norwegian cultural background). Also, Ma et al. (2009) observed that Chinese verbs were found to be more imageable than English verbs. In line with the frameworks of Paivio and Barsalou discussed in the Introduction, perceptual and sensorimotor features associated with a specific word rely on personal experience which can differ across different cultures.

In sum, this study presents a database providing concreteness, imageability and emotional valence ratings for a set of nouns and verbs. This freely available database should allow researchers to more fully control the different semantic dimensions associated with verbal material in cognitive and psycholinguistic experiments. The database currently includes a relatively limited set of nouns and verbs that can be enlarged by future studies.

Article 2 - Appendices

APPENDIX 1 – Instructions for the emotional valence, concreteness and imageability questionnaires

Instructions for the emotional valence questionnaire

Lors de cette étude, il vous sera présenté des mots et des verbes de la langue française. Nous allons vous demander de juger la valeur émotionnelle que vous évoquent ces mots.
Pour ce faire, nous vous demanderons de répondre sur une échelle allant de 1 à 5:
1 = Très négatif ; 2 = Assez négatif ; 3 = Neutre ; 4 = Assez positif ; 5 = Très positif
N'hésitez pas à utiliser toutes les réponses possibles de l'échelle.
Pensez par exemple au mot « charité ». Ce mot va sans doute vous sembler très positif, il obtiendra une note de « 5, très positif ». En revanche, le mot « table » vous semblera peut-être neutre et obtiendra une note de « 3, neutre » tandis que le mot « trahison » pourrait obtenir une note de « 1, très négatif ». De même, un verbe comme « offrir » vous semblera probablement très positif. Un autre comme « s'asseoir » vous semblera peut-être plus neutre, tandis qu'un dernier, comme « trahir » vous semblera très négatif
Attention, il ne s'agit pas de l'image que vous vous faites de ces mots et verbes, mais d'évaluer quelle valeur émotionnelle vous leurs attribuez.
Pour chaque mot présenté, évaluez son niveau de valeur émotionnelle en utilisant toute l'échelle.

English translation:
In this study, you will be presented with words and verbs from the French language. We will ask you to judge the emotional value associated with these words
To do this, we will ask you to answer on a scale from 1 to 5:
1 = Very negative; 2 = Somewhat negative; 3 = Neutral; 4 = Somewhat positive; 5 = Very positive
Please consider to use all the possible answers on the scale.
For example, think of the word "charity". This word will probably sound very positive to you, you will rate it as "5, very positive". The word "table" might seem neutral and it will get a score of "3, neutral" and the word "treason" might get a score of "1, very negative". Similarly, a verb like "to offer" will probably sound very

positive. You will probable the "to sit down" as being more neutral, while "to betray" will be rated as very negative.
Be careful, you should not consider the image you have of these nouns and verbs, but the level of emotional value you associate to them.
For each word presented, assess its level of emotional value using the entire scale.

Instructions for the concreteness questionnaire

Lors de cette étude, il vous sera présenté des mots et des verbes de la langue française. Nous allons vous demander de juger dans quelle mesure ils vous semblent concrets.
Pour ce faire, nous vous demanderons de répondre sur une échelle allant de 1 à 5 :
1 = Pas/Très peu concret ; 2 = Peu concret ; 3 = Moyennement concret ; 4 = Assez bien concret ; 5 = Fortement concret
Mots et verbes diffèrent selon leur niveau d'abstraction. Certains mots font référence à des objets palpables, des matériaux ou des personnes qui peuvent être facilement perçus par nos sens. :
Nous pouvons considérer de tels mots comme des mots concrets. D'autres mots font référence à des concepts abstraits. Ces mots abstraits, au contraire des mots concrets, ne font donc pas référence aussi aisément à des objets palpables, des matériaux ou des personnes qui peuvent être facilement perçus par nos sens.
De même, certains verbes font référence à des actions concrètes, facilement perceptibles par nos sens, et produisant des conséquences tangibles. D'autres font références à des activités abstraites, difficilement perceptibles lorsqu'elles sont réalisées.
En résumé, mots et verbes varient dans leur capacité à être considérés comme concrets. Certains nous semblent plus concrets et ce, très rapidement et très spontanément, tandis que d'autres nous évoquent des concepts plus abstraits, qui nécessitent un certain délai ou, même que l'on ne peut pas du tout concrétiser.
Les éléments qui vous sembleront très concrets auront un haut score de concrétude, ceux qui ne vont sembleront pas du tout concret auront un faible score de concrétude.
Pensez par exemple au mot « chat ». Ce mot va sans doute vous sembler très concret rapidement, il obtiendra une cote élevée de concrétude. En revanche, le mot « loyauté » vous semblera peu concret, il obtiendra une cote faible de concrétude. De même, le verbe « cuisiner » désigne une action qui vous paraitra sans doute

concrète, alors même que le verbe « penser » vous semblera sans doute désigner une action moins concrète.
Attention, il ne s'agit pas de l'image que vous vous faites des mots, mais d'évaluer à quel point ils représentent un concept concret.

English translation:
In this study, you will be presented with nouns and verbs from the French language. We ask you to judge to what extent they seem concrete to you.
To do this, we ask you to answer on a scale from 1 to 5:
1 = Not/very little concrete; 2 = Not very concrete; 3 = Moderately concrete; 4 = Fairly concrete; 5 = Strongly concrete.
Nouns and verbs differ in their level of abstraction. Some nouns refer to palpable objects, materials, or people, that can be easily perceived by our senses.:
We can consider such nouns as concrete words. Other nouns refer to abstract concepts. These abstract nouns, unlike concrete nouns, do not refer as easily to palpable objects, materials or persons that can be easily perceived by our senses.
Similarly, some verbs refer to concrete actions, easily perceived by our senses, and producing tangible consequences. Others refer to abstract activities that are difficult to perceive when performed.
In summary, nouns and verbs vary in their level of concreteness. Some are very quickly and spontaneously identified as being rather concrete, while others evoke more abstract concepts, for which a concrete representation cannot be reached or only after a certain amount of time.
The items that seem very concrete will have a high concreteness score, those that do not seem concrete at all will have a very low concreteness score.
Think for example of the word "cat". This word will probably quickly seem very concrete to you, so it will get a high concreteness score. On the other hand, the word "loyalty" will not seem very concrete, and you will give it a low concreteness score. In the same way, the verb "to cook" designates an action that will undoubtedly seem concrete to you, whereas the verb "to think" will undoubtedly seem to you as designating a less concrete action.
Be careful, you should not consider the image you have of the words, but the extent to which they seem to represent a concrete concept to you.

Instructions for the imageability questionnaire

Ainsi, les mots et les verbes varient en termes d'imageabilité : Pour certains d'entre eux il est facile, rapide et spontané de former une image mentale leur correspondant. D'autre en revanche ne vont évoquer une image mentale que lentement, difficilement, voir même ne vont pas en évoquer du tout.
Les mots et verbes qui, pour vous, provoquent l'apparition d'une image mentale très rapidement et très facilement obtiendront une cote élevée en valeur d'imagerie; les mots et verbes qui provoquent l'apparition de cette image avec difficulté ou encore ne provoquent l'apparition d'aucune image obtiendront une cote faible de valeur d'imagerie.
Ainsi, il pourra être noté selon l'échelle suivante:
1 : Pas/Très peu imageable ; 2 : Peu imageable ; 3 : Moyennement imageable ; 4 : Assez bien imageable ; 5 : Fortement imageable
Pensez par exemple au mot « chat ». Il est sans doute facile et rapide pour vous de former une image mentale correspondant à ce mot. En conséquence, le mot chat obtiendra une note élevée d'imagerie (5 : fortement imageable). En revanche, il vous sera sans doute plus difficile et long de former une image mentale correspondant au mot « loyauté ». Ce mot obtiendra donc une faible note d'imagerie (1 : très peu imageable). De la même façon, le verbe « cuisiner » fait référence à une action qui vous paraitra sans doute facilement et rapidement imageable. A l'inverse, le verbe « penser » n'évoquera sans doute une image qu'avec difficulté.

English translation:
Nouns and verbs vary in terms of imageability: for some of them a mental image is formed easily, quickly and spontaneously. Others, on the other hand, will evoke a mental image only slowly, with difficulty, or even not at all.
The nouns and verbs that, for you, generate a mental image very quickly and very easily will obtain a high imageability rating; the nouns and verbs that generate a mental image with more difficulty or not at all will obtain a low imageability rating..
Thus, the word will be scored according to the following scale:
1: Not/Very poorly imageable; 2: Poorly imageable; 3: Moderately imageable; 4: Well imageable; 5: Strongly imageable.
Think of the word "cat" for example. It is probably easy and quick for you to form a mental image corresponding to this word. As a result, the word cat will get a high imageability score (5: strongly imageable). On the other hand, it will probably be

more difficult and time-consuming for you to form a mental image corresponding to the word "loyalty". Therefore, this word will get a low imageability score (1: Not/Very poorly imageable). In the same way, the verb "to cook" refers to an action that you will probably find easy and quick to represent as an image. Conversely, the verb "to think" will probably only evoke an image with difficulty.

APPENDIX 2. Items

Items	Phonology	Translation	Category	Imageability	Concretness	Emotionnal Valence	Letters	puorth	puphon	Syllables	Lexique383 freqfilms2
accroupir	akRupiR	squat	V	4,435294118	4,26744186	2,941860465	9	9	7	3	0,09
acquiescer	akjese	nod	V	4,023529412	4,069767442	3,569767442	10	10	4	3	0,18
adopter	adOpte	adopt	V	2,458823529	3,38372093	3,953488372	7	6	6	3	7,25
agripper	agRipe	grab	V	4,141176471	4,511627907	2,686046512	8	8	6	3	0,44
allonger	al§Ze	extend	V	4,2	4,302325581	3,406976744	8	8	5	3	9,96
allumer	alyme	lighting	V	4,435294118	4,337209302	3,302325581	7	7	5	3	11,98
allumer une allumette		to light a match	V	4,8	4,860465116	3,197674419					
altérer	alteRe	alter	V	1,835294118	2,709302326	2,197674419	7	6	6	3	0,83
appeler	ap°le	call	V	4,411764706	4,558139535	3,279069767	7	7	5	3	192,69
applaudir	aplodiR	applaud	V	4,905882353	4,779069767	4,534883721	9	9	7	3	3,16
asseoir	aswaR	asseoir	V	4,105882353	4,290697674	3,197674419	7	5	5	2	65,1
attaquer	atake	attack	V	3,776470588	4,209302326	1,953488372	8	8	5	3	25,91

attraper	atRape	catch	V	4,529411765	4,465116279	3,244186047	8	8	6	3	35,32
augmenter	ogm@te	increase	V	2,717647059	3,395348837	3,802325581	9	8	6	3	9,94
avancer	av@se	advance	V	4,164705882	4,011627907	3,953488372	7	7	5	3	22,65
avoir peur		be afraid	V	3,858823529	3,186046512	1,697674419					
balayer	baleje	sweep	V	4,752941176	4,709302326	2,872093023	7	7	5	3	3,4
boire	bwaR	drink	V	4,858823529	4,930232558	3,558139535	5	4	4	1	142,15
bondir	b§diR	leap	V	4,376470588	4,348837209	3,279069767	6	6	5	2	2,11
boucher	buSe	butcher	V	3,541176471	4,093023256	2,406976744	7	7	4	2	5,33
bouger	buZe	move	V	4,235294118	4,418604651	3,662790698	6	6	4	2	44,32
briller	bRije	shine	V	3,505882353	3,837209302	4,406976744	7	6	5	2	5,08
brosser	bRose	brush	V	4,6	4,569767442	3,034883721	7	7	5	2	2,76
brûler	bRyle	burn	V	4,376470588	4,61627907	1,755813953	6	6	5	2	23,14
calculer	kalkyle	calculate	V	3,376470588	4,197674419	3,104651163	8	8	7	3	3,09
caresser	kaRese	caressing	V	4,647058824	4,627906977	4,290697674	8	8	5	3	5,66
casser	kase	break	V	4,447058824	4,430232558	1,825581395	6	6	4	2	36,24
citer	site	quote	V	2,211764706	3,662790698	3,093023256	5	5	4	2	4,38
clouer	klue	nail	V	4,305882353	4,709302326	2,976744186	6	6	4	2	1,4
colorier	koloRje	coloring	V	4,764705882	4,848837209	3,744186047	8	7	7	3	0,25

compter	k§te	counting	V	3,941176471	4,313953488	3,104651163	7	7	4	2	45,05
conduire	k§d8iR	driving	V	4,894117647	4,674418605	3,406976744	8	7	6	2	60,56
congeler	k§Z°le	freezing	V	3,823529412	4,430232558	2,930232558	8	7	4	3	1,12
coudre	kudR	sewing	V	4,635294118	4,720930233	3,372093023	6	6	4	1	4,83
couper	kupe	cutting	V	4,670588235	4,465116279	2,546511628	6	6	4	2	41,45
courir	kuRiR	running	V	4,894117647	4,813953488	3,360465116	6	5	4	2	47,19
danser	d@se	dancing	V	4,823529412	4,720930233	4,453488372	6	6	4	2	70,06
déborder	debORde	overflow	V	3,694117647	3,825581395	2,197674419	8	8	7	3	1,78
décamper	dek@pe	scramble	V	3,258823529	3,651162791	2,255813953	8	6	5	3	0,81
décliner	dekline	decline	V	2,364705882	3,244186047	2,372093023	8	7	7	3	0,58
dégoûter	degute	deflategate	V	2,882352941	3,23255814	1,523255814	8	7	6	3	0,66
déposer	depoze	depositing	V	4,094117647	4,372093023	3,034883721	7	7	6	3	15,03
déraper	deRape	slipping	V	3,705882353	4,104651163	2,197674419	7	6	6	3	0,53
descendre	des@dR	descend	V	4,364705882	4,279069767	2,976744186	9	8	6	2	65,28
dessiner	desine	draw	V	4,811764706	4,720930233	3,88372093	8	7	6	3	9,1
dévaler	devale	down	V	3,376470588	3,790697674	2,639534884	7	7	6	3	0,29
dévisser	devise	unscrew	V	4,211764706	4,686046512	3	8	7	6	3	0,48
donner	done	give	V	4,058823529	4,209302326	4	6	6	4	2	233,3

dormir	dORmiR	sleeping	V	4,764705882	4,581395349	4,127906977	6	6	6	2	160,77
douter	dute	doubt	V	2,623529412	3,034883721	1,906976744	6	6	4	2	12,64
durer	dyRe	last	V	1,811764706	2,61627907	3,127906977	5	5	4	2	20,59
écraser	ekRaze	crush	V	4,329411765	4,488372093	1,825581395	7	7	6	3	16,75
écrire	ekRiR	writing	V	4,776470588	4,790697674	3,627906977	6	5	5	2	84,14
effacer	efase	erase	V	4,082352941	4,220930233	2,476744186	7	7	5	3	10,05
embrasser	@bRase	embrace	V	4,847058824	4,604651163	4,627906977	9	9	6	3	43,91
enjamber	@Z@be	embrace	V	4,447058824	4,511627907	3,127906977	8	8	5	3	0,42
enlacer	@lase	embrace	V	4,741176471	4,406976744	4,418604651	7	7	5	3	0,97
enregistrer	@R°ZistRe	record	V	3,047058824	3,779069767	3,093023256	11	11	9	4	7,58
envisager	@vizaZe	consider	V	1,988235294	2,546511628	3,441860465	9	9	7	4	4,83
escalader	Eskalade	escalate	V	4,741176471	4,755813953	3,337209302	9	9	8	4	2,19
espérer	EspeRe	hope	V	2,094117647	2,511627907	3,848837209	7	6	6	3	15,65
essuyer	es8ije	wipe	V	4,576470588	4,465116279	2,872093023	7	7	6	3	3,39
étinceler	et5s°le	sparkling	V	3,058823529	3,174418605	4,395348837	9	8	7	4	0,07
être déçu		to be disappointed	V	3,011764706	2,988372093	1,395348837					

être dégouté		to be disgusted	V	3,4	3,360465116	1,406976744					
evoluer	evol8e	evolve	V	2,423529412	2,837209302	4,348837209	7	6	5	3	2,9
faire des pompes		to do push-ups	V	4,788235294	4,802325581	3,081395349					
faire rebondir		bounce	V	4,211764706	4,337209302	3,244186047					
faire signe		waving	V	4,564705882	4,302325581	3,581395349					
faire une passe		passing the ball	V	4,458823529	4,523255814	3,465116279					
fermer	fERme	close	V	4,494117647	4,406976744	2,720930233	6	6	5	2	48,85
fermer une bouteille		close a bottle	V	4,8	4,88372093	3,011627907					
flotter	flote	float	V	4,2	4,279069767	3,372093023	7	7	5	2	3,16
fondre	f§dR	melt	V	3,8	3,697674419	2,837209302	6	6	4	1	8,05
fouler	fule	whip	V	2,670588235	3,325581395	2,639534884	6	6	4	2	0,65
frapper	fRape	strike	V	4,764705882	4,488372093	1,465116279	7	7	5	2	37,08
frotter	fRote	rub	V	4,352941176	4,581395349	2,930232558	7	7	5	2	4,01
gommer	gome	scrub	V	4,647058824	4,558139535	2,88372093	6	6	4	2	0,26

gratter	gRate	scratch	V	4,435294118	4,534883721	2,790697674	7	7	5	2	5,03
griffer	gRife	scratch	V	4,611764706	4,709302326	1,918604651	7	7	5	2	0,64
inviter	5vite	invite	V	2,882352941	3,534883721	4,11627907	7	7	5	3	22,63
jeter	Z°te	throw	V	4,470588235	4,5	2,38372093	5	5	4	2	59,28
jongler	Z§gle	juggling	V	4,729411765	4,651162791	3,337209302	7	7	5	2	0,83
lancer	l@se	throwing	V	4,729411765	4,558139535	3,023255814	6	6	4	2	18,56
lever	l°ve	lift	V	4,188235294	4,220930233	3,26744186	5	5	4	2	35,9
louer	lwe	rent	V	2,329411765	3,569767442	3,127906977	5	5	3	1	15,03
manger	m@Ze	eat	V	4,870588235	4,860465116	3,941860465	6	6	4	2	207,63
maquiller	makije	make-up	V	4,694117647	4,290697674	3,26744186	9	9	6	3	3,1
marcher	maRSe	walk	V	4,788235294	4,813953488	3,406976744	7	7	5	2	85,34
monter	m§te	go up	V	4,447058824	4,465116279	3,197674419	6	6	4	2	85,7
montrer	m§tRe	show	V	4,023529412	4,23255814	3,23255814	7	7	5	2	136,2
neiger	neZe	snow	V	4,447058824	4,476744186	4,034883721	6	6	4	2	0,59
nettoyer	netwaje	clean	V	4,529411765	4,534883721	2,976744186	8	8	7	3	30,28
nuancer	n8@se	shade	V	1,894117647	2,569767442	3,279069767	7	7	5	2	0,01
organiser	ORganize	organize	V	2,870588235	3,523255814	3,639534884	9	9	8	4	13,93
ouvrir	uvRiR	open	V	4,517647059	4,453488372	3,418604651	6	6	5	2	79,61

passer	pase	pass	V	3,164705882	3,034883721	3,034883721	6	6	4	2	345,68
pédaler	pedale	pedal	V	4,835294118	4,779069767	3,209302326	7	7	6	3	0,37
peindre	p5dR	painting	V	4,858823529	4,73255814	3,744186047	7	5	3	1	12,75
permettre	pERmEtR	allow	V	1,941176471	2,686046512	3,709302326	9	6	5	2	26,32
piger	piZe	piger	V	2,176470588	3,011627907	3,372093023	5	5	4	2	1,78
pleurer	pl2Re	crying	V	4,823529412	4,581395349	1,639534884	7	7	5	2	61,6
pleuvoir	pl2vwaR	raining	V	4,647058824	4,523255814	2,720930233	8	6	5	2	7,98
pointer	pw5te	pointing	V	4,188235294	4,209302326	2,825581395	7	7	5	2	4,63
porter	poRte	carry	V	4,411764706	4,488372093	3,174418605	6	6	4	2	79,04
pousser	puse	pushing	V	4,6	4,325581395	2,755813953	7	7	4	2	27,51
préjuger	pReZyZe	prejudge	V	1,741176471	2,279069767	1,581395349	8	7	6	3	0,02
publier	pyblije	publish	V	2,835294118	3,546511628	3,38372093	7	7	7	3	6,85
ramasser	Ramase	pick up	V	4,564705882	4,627906977	2,930232558	8	8	6	3	13,15
ramper	R@pe	crawl	V	4,647058824	4,604651163	2,558139535	6	6	4	2	3,32
rebondir	R°b§diR	bounce	V	4,129411765	4,23255814	3,546511628	8	8	7	3	1,56
reculer	R°kyle	reverse	V	4,364705882	4,581395349	2,441860465	7	6	6	3	6,83
refermer	R°fERme	close	V	4,129411765	4,360465116	2,61627907	8	6	6	3	3,26
refléter	R°flete	reflect	V	2,823529412	3,139534884	3,220930233	8	5	5	3	0,8

refuser	R°fyze	refuse	V	3,364705882	3,76744186	2,372093023	7	6	5	3	21,34
regrouper	R°gRupe	regroup	V	3,2	3,976744186	3,581395349	9	9	7	3	0,59
renseigner	R@seNe	renseigner	V	2,752941176	3,511627907	3,558139535	10	10	4	3	9,08
résister	Reziste	resist	V	2,847058824	3,372093023	3,5	8	7	7	3	17,54
réunir	ReyniR	reunite	V	3,058823529	3,558139535	4,046511628	6	6	6	3	9,11
rêver	Reve	dream	V	3,588235294	3,476744186	4,581395349	5	5	4	2	20,8
rire	RiR	laughing	V	4,858823529	4,523255814	4,860465116	4	3	3	1	63,29
s’accroupir		crouch	V	4,576470588	4,848837209	2,918604651					
s’agenouiller		kneeling	V	4,552941176	4,720930233	2,906976744					
s'asseoir		sitting	V	4,776470588	4,755813953	3,244186047					
s’enlacer		hugging	V	4,505882353	4,453488372	4,5					
s’'ennuyer		bored	V	3,070588235	3,244186047	1,976744186					
s'allonger		to lie down	V	4,682352941	4,686046512	3,755813953					
saluer	sal8e	salute	V	4,517647059	4,546511628	3,802325581	6	6	5	2	11,85
saupoudrer	sopudRe	sprinkle	V	4,294117647	4,337209302	3,313953488	10	10	7	3	0,1
sauter	sote	jump	V	4,835294118	4,651162791	3,209302326	6	6	4	2	57,89
sautiller	sotije	jumping	V	4,552941176	4,604651163	3,895348837	9	9	6	3	0,3
scotcher	skOtSe	scotch	V	4,188235294	4,453488372	3,046511628	8	7	6	2	0,17

se baisser		bending down	V	4,635294118	4,744186047	2,872093023					
se brosser les dents		brush teeth	V	4,894117647	4,88372093	3,5					
se disputer		arguing	V	4,188235294	4,302325581	1,302325581					
se lever		getting up	V	4,682352941	4,744186047	3,290697674					
se maquiller		putting on make-up	V	4,776470588	4,73255814	3,453488372					
se pencher		bending over	V	4,482352941	4,651162791	2,965116279					
sécher	seSe	drying	V	3,564705882	4,325581395	3,023255814	6	6	4	2	5,84
secouer	s°kwe	shaking	V	4,411764706	4,313953488	2,418604651	7	7	5	2	4,5
sembler	s@ble	seem	V	1,682352941	2,313953488	2,837209302	7	6	5	2	6,01
serrer	seRe	shake	V	4,341176471	4,302325581	3,093023256	6	6	4	2	13,68
serrer la main		shake hands	V	4,870588235	4,848837209	3,418604651					
shooter	shooter	shoot	V	3,858823529	3,906976744	2,76744186	7	7	4	2	1,88
signer	signer	sign	V	4,482352941	4,511627907	3,197674419	6	6	4	2	29,25
songer	songer	sigh	V	2,635294118	2,511627907	3,441860465	6	6	4	2	5,56
souffrir	souffrir	suffering	V	3,482352941	3,279069767	1,23255814	8	7	5	2	34,26
souligner	souligner	underline	V	4,411764706	4,337209302	3,023255814	9	6	4	3	1,65

survenir	survenir	happen	V	2,035294118	2,941860465	2,860465116	8	7	7	3	0,8
taper	taper	type	V	4,611764706	4,11627907	1,697674419	5	5	4	2	19,15
taper au clavier		type on keyboard	V	4,858823529	4,953488372	3,058139535					
tartiner	taRtine	spread	V	4,576470588	4,674418605	3,453488372	8	8	7	3	0,41
téléphoner	telefone	phone	V	4,717647059	4,860465116	3,151162791	10	10	8	4	20,22
tirer	tiRe	shoot	V	4,423529412	4,302325581	2,639534884	5	5	4	2	113,71
tomber	t§be	drop	V	4,623529412	4,523255814	1,941860465	6	6	4	2	180,25
tordre	tORdR	twisting	V	4,364705882	4,325581395	2,23255814	6	5	5	1	2,77
toucher	tuSe	touching	V	4,435294118	4,674418605	3,337209302	7	7	4	2	49,43
tourner	tuRne	turning	V	4,364705882	4,465116279	3,069767442	7	7	5	2	51,05
tracer	tRase	tracing	V	3,988235294	4,337209302	3,058139535	6	6	5	2	2,08
tricoter	tRikote	knitting	V	4,741176471	4,779069767	3,209302326	8	8	7	3	1,37
trottiner	tRotine	trotting	V	4,505882353	4,604651163	3,325581395	9	9	7	3	0,03
valser	valse	waltzing	V	3,858823529	3,825581395	3,546511628	6	6	5	2	1,33
verser	vERse	pouring	V	4,541176471	4,604651163	3,069767442	6	6	5	2	4,62
vibrer	vibRe	vibrate	V	3,435294118	3,593023256	3,430232558	6	6	5	2	2,06
visser	vise	screwing	V	4,482352941	4,674418605	3,058139535	6	6	4	2	1,45

abeille	abEj	bee	N	4,894117647	4,860465116	3,627906977	7	4	4	2	3,53
adresse	adREs	adress	N	2,918604651	4,069767442	3,069767442	7	7	5	2	67,28
affiche	afiS	poster	N	4,674418605	4,581395349	3	7	7	4	2	5,38
agilité	aZilite	agility	N	2,534883721	2,930232558	3,860465116	7	5	5	4	1
album	albOm	album	N	4,270588235	4,453488372	3,651162791	5	5	5	2	9,36
allumette	alymEt	match	N	4,858823529	4,872093023	3,069767442	9	7	5	3	4,43
alphabet	alfabE	alphabet	N	4,197674419	4,197674419	3,209302326	8	7	6	3	3,14
ampoule	@pul	light bulb	N	4,905882353	4,802325581	3,174418605	7	7	4	2	4,8
animal	animal	animal	N	4,511627907	4,593023256	4	6	6	6	3	36,89
arc	aRk	bow	N	4,788235294	4,360465116	3,058139535	3	3	3	1	4,52
argent	aRZ@	silver	N	4,709302326	4,313953488	3,581395349	6	6	4	2	515,04
attache	ataS	attachment	N	3,244186047	3,860465116	3,034883721	7	7	4	2	1,82
automne	otOn	fall	N	3,88372093	3,930232558	3,674418605	7	7	4	2	16,88
avocat	avoka	lawyer	N	4,651162791	4,441860465	3,11627907	6	6	5	3	89,28
barbe	baRb	beard	N	4,918604651	4,790697674	3,069767442	5	5	4	1	23,4
bateau	bato	boat	N	4,870588235	4,802325581	3,395348837	6	6	4	2	106,55
bâtiment	batim@	building	N	4,744186047	4,744186047	3,081395349	8	5	6	3	22,73
bébé	bebe	baby	N	4,870588235	4,709302326	3,813953488	4	4	4	2	173,82

bénéfice	benefis	profit	N	2,186046512	2,976744186	4,011627907	8	8	7	3	4,31
berceau	bERso	crib	N	4,705882353	4,813953488	3,546511628	7	6	5	2	6,72
biscuit	bisk8i	cookie	N	4,848837209	4,848837209	3,88372093	7	7	6	2	4,75
blaireau	blERo	badger	N	4,546511628	4,569767442	2,755813953	8	7	5	2	2,64
bombe	b§b	bomb	N	4,61627907	4,523255814	1,5	5	5	3	1	48,7
bouche	buS	mouth	N	4,953488372	4,744186047	3,244186047	6	6	3	1	87,75
boue	bu	mud	N	4,546511628	4,651162791	2,662790698	4	4	2	1	15,09
brigand	bRig@	brigand	N	4,011627907	4,139534884	1,906976744	7	7	5	2	2,1
briquet	bRikE	lighter	N	4,835294118	4,802325581	2,744186047	7	7	5	2	9,98
brosse	bROs	brush	N	4,847058824	4,697674419	3,046511628	6	6	4	1	7,29
bureau	byRo	office	N	4,670588235	4,5	2,744186047	6	6	4	2	156,68
café	kafe	coffee	N	4,823529412	4,546511628	3,23255814	4	4	4	2	157,56
cambriolage	k@bRijolaZ	burglary	N	3,697674419	4,139534884	1,453488372	11	9	9	4	6,6
cancer	k@sER	cancer	N	2,709302326	3,813953488	1,104651163	6	6	5	2	22,34
capacité	kapasite	capacity	N	2,069767442	2,627906977	3,76744186	8	8	5	4	9,42
centre	s@tR	center	N	3,372093023	3,244186047	3,058139535	6	6	4	1	53,46
cerise	s°Riz	cherry	N	4,965116279	4,906976744	3,779069767	6	6	5	2	2,75
chant	S@	song	N	3,744186047	3,790697674	4,011627907	5	5	2	1	17,64

chantier	S@tje	construction site	N	4,441860465	4,244186047	2,802325581	8	7	4	2	9,93
chat	Sa	cat	N	4,952941176	4,906976744	4,26744186	4	4	2	1	57,71
châtaigne	SatEN	chestnut	N	4,755813953	4,76744186	3,290697674	9	9	5	2	0,55
château	Sato	castle	N	4,813953488	4,779069767	3,569767442	7	7	4	2	40,51
cheminée	S°mine	fireplace	N	4,847058824	4,76744186	3,569767442	8	7	6	3	9,99
cheveux	S°v2	hair	N	4,811764706	4,779069767	3,5	7	0	4	2	116,16
cheville	S°vij	ankle	N	4,837209302	4,744186047	2,918604651	8	8	5	2	8,79
chien	Sj5	dog	N	4,976470588	4,813953488	4,023255814	5	5	3	1	158,77
chocolat	Sokola	chocolate	N	4,906976744	4,813953488	4,302325581	8	8	6	3	27,74
clef	kle	key	N	4,894117647	4,686046512	3,360465116	4	4	3	1	14,61
clou	klu	nail	N	4,859575923	4,843023256	2,843023256	4	4	3	1	7,79
collection	kolEksj§	collection	N	3,465116279	3,813953488	3,360465116	10	10	8	3	16,25
collier	kolje	collar	N	4,894117647	4,790697674	3,546511628	7	6	4	2	17,79
consonne	k§sOn	consonant	N	3,348837209	4,244186047	3	8	7	5	2	0,2
copie	kopi	copy	N	3,569767442	4,093023256	2,88372093	5	5	4	2	16,88
coq	kOk	rooster	N	4,870588235	4,825581395	3,162790698	3	3	3	1	10,74
côté	kote	side	N	2,848837209	3,534883721	3	4	4	4	2	250,51

course	kuRs	race	N	4,034883721	3,802325581	3,174418605	6	6	4	1	40,45
couteau	kuto	knife	N	4,952941176	4,825581395	2,5	7	7	4	2	51,08
crapaud	kRapo	toad	N	4,848837209	4,779069767	2,813953488	7	7	5	2	9,6
cruche	kRyS	pitcher	N	4,282352941	4,581395349	2,860465116	6	6	4	1	2,92
cuisine	k8izin	kitchen	N	4,686046512	4,581395349	3,860465116	7	7	6	2	85,08
culture	kyltyR	culture	N	2,686046512	2,872093023	4,023255814	7	7	6	2	18,76
délit	deli	crime	N	2,441860465	3,081395349	1,709302326	5	5	4	2	11,35
dialogue	djalOg	dialogue	N	2,953488372	3,046511628	3,662790698	8	8	5	2	14,11
eau	o	water	N	4,588235294	4,23255814	4,093023256	3	3	1	1	290,61
éclair	eklER	lightning	N	4,674418605	4,058139535	3,174418605	6	6	5	2	7,86
école	ekOl	school	N	4,709302326	4,372093023	3,465116279	5	5	4	2	197,04
élan	el@	momentum	N	3,930232558	3,76744186	3,38372093	4	4	3	2	4,61
ennui	@n8i	boredom	N	2,465116279	2,639534884	1,895348837	5	5	4	2	14,76
enveloppe	@v°lOp	envelope	N	4,88372093	4,709302326	3,046511628	9	9	6	3	11,4
environnement	@viROn°m@	environment	N	2,825581395	3,11627907	3,720930233	13	13	9	5	10,07
épingle	ep5gl	pin	N	4,651162791	4,697674419	2,918604651	7	7	5	2	3,29
esprit	EspRi	mind	N	2,360465116	2,511627907	3,720930233	6	6	5	2	131,7
explosion	Eksplozj§	explosion	N	4,593023256	4,220930233	1,686046512	9	8	8	3	23,11

faculté	fakylte	faculty	N	2,965116279	2,604651163	3,61627907	7	7	7	3	5,93
farine	faRin	flour	N	4,802325581	4,813953488	3,244186047	6	6	5	2	7,93
feu	f2	fire	N	4,761833105	4,131782946	3,034883721	3	3	2	1	215,87
feuille	f9j	leaf	N	4,837209302	4,61627907	3,186046512	7	7	3	1	13,24
flèche	flES	arrow	N	4,811764706	4,558139535	2,872093023	6	3	4	1	8,21
fleur	fl9R	flower	N	4,905882353	4,76744186	4,162790698	5	5	4	1	25,2
fourchette	fuRSEt	fork	N	4,917647059	4,813953488	3,186046512	10	9	6	2	4,98
fraise	fREz	strawberry	N	4,930232558	4,88372093	3,953488372	6	6	4	1	5,28
gant	g@	glove	N	4,811764706	4,825581395	3,069767442	4	4	2	1	9,86
gâteau	gato	cake	N	4,930232558	4,76744186	4,034883721	6	5	4	2	42,33
géranium	ZeRanjOm	geranium	N	4,38372093	4,593023256	3,406976744	8	6	5	3	0,77
gorille	goRij	gorilla	N	4,882352941	4,837209302	3,26744186	7	4	4	2	3,55
goût	gu	taste	N	2,395348837	3,127906977	3,906976744	4	4	2	1	50,51
grenade	gR°nad	pomegranate	N	4,744186047	4,38372093	1,930232558	7	7	6	2	6,32
grue	gRy	crane	N	4,674418605	4,651162791	2,965116279	4	4	3	1	3,54
habileté	abil°te	skill	N	2,011627907	2,569767442	3,662790698	8	7	6	4	2,03
heure	9R	time	N	2,870588235	2,941860465	2,941860465	5	5	2	1	415,4
horloge	ORlOZ	clock	N	4,882352941	4,825581395	3,11627907	7	7	5	2	9,37

horoscope	oRoskOp	horoscope	N	3,534883721	3,302325581	3,023255814	9	4	4	3	2,47
imitation	imitasj§	imitation	N	2,779069767	3,26744186	3	9	8	6	4	3,33
index	5dEks	index	N	4,081395349	3,918604651	2,976744186	5	5	5	2	2,18
juge	ZyZ	judge	N	3,918604651	4,290697674	2,686046512	4	4	3	1	56,4
justice	Zystis	justice	N	2,697674419	2,686046512	3,651162791	7	7	6	2	50,96
lait	lE	milk	N	4,811764706	4,651162791	3,244186047	4	4	2	1	59,41
laitue	lety	lettuce	N	4,717647059	4,755813953	3,197674419	6	5	4	2	1,97
lettre	lEtR	letter	N	4,651162791	4,511627907	3,302325581	6	6	4	1	108,79
lieu	lj2	place	N	2,941860465	3,209302326	3,046511628	4	4	3	1	153,12
livre	livR	book	N	4,860465116	4,837209302	3,953488372	5	5	4	1	112,43
lumière	lymjER	light	N	3,905882353	3,465116279	4,395348837	7	5	4	2	116,02
maison	mEz§	house	N	4,895348837	4,837209302	4,034883721	6	6	4	2	570,3
maladie	maladi	disease	N	2,755813953	3,523255814	1,220930233	7	7	6	3	52,18
manoir	manwaR	manor	N	4,61627907	4,639534884	2,976744186	6	5	4	2	5,87
marécage	maRekaZ	swamp	N	4,337209302	4,453488372	2,372093023	8	8	7	3	2,31
marteau	maRto	hammer	N	4,917647059	4,860465116	2,848837209	7	7	5	2	11,84
matin	mat5	morning	N	2,988235294	3,093023256	3,593023256	5	5	4	2	265,03
mer	mER	sea	N	4,777564979	4,337209302	4,226744186	3	3	3	1	99,49

milieu	milj2	middle	N	3,162790698	3,127906977	3,069767442	6	5	5	2	68,6
moufle	mufl	muffle	N	4,705882353	4,802325581	3,104651163	6	6	4	1	0,28
moulin	mul5	mill	N	4,8	4,662790698	3,26744186	6	6	4	2	6,8
mousse	mus	moss	N	4,476744186	4,302325581	3,569767442	6	6	3	1	6,24
muguet	mygE	lily of the valley	N	4,73255814	4,73255814	3,848837209	6	6	3	2	0,38
mur	myR	wall	N	4,848837209	4,76744186	2,88372093	3	3	3	1	58,9
musique	myzik	music	N	3,744186047	3,930232558	4,546511628	7	7	5	2	168,89
neige	nEZ	snow	N	4,764705882	4,534883721	4	5	5	3	1	37,52
note	nOt	note	N	4,348837209	3,662790698	2,953488372	4	4	3	1	33,42
oiseau	wazo	bird	N	4,837209302	4,813953488	3,755813953	6	6	4	2	43,78
orchestre	ORkEstR	orchestra	N	4,627906977	4,61627907	3,662790698	9	9	7	2	13,71
page	paZ	page	N	4,546511628	4,604651163	3,197674419	4	4	3	1	25,16
palais	palE	palace	N	4,593023256	4,453488372	3,418604651	6	5	4	2	29,55
papier	papje	paper	N	4,76744186	4,662790698	3,151162791	6	6	5	2	56,32
partition	paRtisj§	score	N	4,337209302	4,38372093	3,38372093	9	8	7	3	2,88
pelle	pEl	shovel	N	4,917647059	4,744186047	2,76744186	5	5	3	1	8,75
pensée	p@se	thought	N	2,337209302	2,441860465	3,88372093	6	5	4	2	26,25

pépin	pep5	seed	N	4,674418605	4,372093023	2,581395349	5	5	4	2	4,31
perceuse	pERs2z	drill	N	4,755813953	4,73255814	2,848837209	8	0	0	2	0,97
perle	pERl	bead	N	4,658823529	4,604651163	3,76744186	5	5	4	1	4,13
photo	foto	photo	N	4,658823529	4,627906977	4	5	5	4	2	122,47
pneu	pn2	tire	N	4,905882353	4,825581395	2,941860465	4	4	3	1	5,64
poignée	pwaNe	handle	N	4,776470588	4,488372093	3,023255814	7	6	5	2	11,65
poire	pwaR	pear	N	4,882352941	4,825581395	3,348837209	5	5	4	1	5,67
pomme	pOm	apple	N	4,952941176	4,88372093	3,546511628	5	5	3	1	19,77
pompier	p§pje	fireman	N	4,837209302	4,825581395	3,744186047	7	6	5	2	2,67
porte	pORt	door	N	4,929411765	4,790697674	3	5	5	4	1	288,39
possibilité	posibilite	possibility	N	1,744186047	2,674418605	3,720930233	11	7	6	5	16,79
poste	pOst	post	N	3,736525308	3,843023256	2,970930233	5	5	4	1	72,64
poster	pOste	poster	N	4,174418605	4,186046512	3,174418605	6	6	5	2	1,6
poule	pul	chicken	N	4,905882353	4,88372093	3,26744186	5	5	3	1	23,5
problème	pRoblEm	problem	N	2,139534884	2,976744186	1,651162791	8	6	6	2	391,2
punaise	pynEz	pin	N	4,593023256	4,511627907	2,546511628	7	7	5	2	1,41
raquette	RakEt	racket	N	4,882352941	4,662790698	3,26744186	8	6	5	2	1,77
rasoir	RazwaR	razor	N	4,837209302	4,790697674	2,755813953	6	4	4	2	8,18

recette	R°sEt	recipe	N	3,941860465	4,325581395	3,534883721	7	5	5	2	9,56
répertoire	RepERtwaR	repertoire	N	3,627906977	4,11627907	3,058139535	10	8	7	3	2,04
réplique	Replik	replica	N	2,093023256	3,26744186	3,081395349	8	8	6	2	6,16
rêve	REv	dream	N	3,26744186	2,581395349	4,476744186	4	4	3	1	99,39
réveil	RevEj	alarm clock	N	4,4	4,186046512	2,720930233	6	6	5	2	18,16
ruche	RyS	hive	N	4,705882353	4,720930233	3,337209302	5	5	3	1	2,64
salade	salad	salad	N	4,917647059	4,779069767	3,23255814	6	6	5	2	15,88
saut	so	jump	N	4,418604651	4,372093023	3,11627907	4	4	2	1	13,53
saxophone	saksofOn	saxophone	N	4,709302326	4,779069767	3,453488372	9	9	7	3	1,3
serrure	seRyR	lock	N	4,729411765	4,720930233	2,976744186	7	7	5	2	7,4
signe	siN	sign	N	3,337209302	3,395348837	3,348837209	5	5	3	1	67,74
singe	s5Z	monkey	N	4,917647059	4,837209302	3,441860465	5	5	3	1	21,59
sirène	siREn	siren	N	4,476744186	4,186046512	3,058139535	6	4	4	2	8,06
ski	ski	ski	N	4,764705882	4,488372093	3,627906977	3	3	3	1	13,84
sol	sOl	ground	N	4,406976744	4,395348837	3,081395349	3	3	3	1	45,83
sommaire	somER	summary	N	3,581395349	3,930232558	2,988372093	8	8	5	2	0,21
son	s§	sound	N	2,61627907	3,534883721	3,61627907	3	3	2	1	39,69
souci	susi	worry	N	2,046511628	2,686046512	1,88372093	5	5	4	2	26,73

tasse	tas	cup	N	4,917647059	4,848837209	3,220930233	5	5	3	1	18,52
tennis	tenis	tennis	N	4,447058824	4,302325581	3,337209302	6	6	5	2	11,37
theatre	teatR	theater	N	4,581395349	4,430232558	3,73255814	7	7	5	2	40,51
timbre	t5bR	stamp	N	4,836183311	4,779069767	3,063953488	6	6	4	1	1,82
travail	tRavaj	work	N	2,752941176	3,069767442	2,755813953	7	7	6	2	367,43
tribunal	tRibynal	court	N	4,186046512	4,360465116	2,38372093	8	8	8	3	35,35
trombone	tR§bOn	trombone	N	4,697674419	4,697674419	3,139534884	8	8	6	2	1,78
tumeur	tym9R	tumor	N	2,895348837	4,046511628	1,174418605	6	5	4	2	6,7
université	ynivERsite	university	N	4,441860465	4,337209302	3,476744186	10	10	10	5	38,22
vache	vaS	cow	N	4,929411765	4,825581395	3,313953488	5	5	3	1	36,24
vase	vaz	vase	N	4,847948016	4,813953488	3,255813953	4	4	3	1	9,83
vent	v@	wind	N	3,423529412	3,662790698	2,61627907	4	4	2	1	71,5
vis	vis	screw	N	4,697674419	4,720930233	2,895348837	3	3	3	1	6,89
vitesse	vitEs	speed	N	2,825581395	3,406976744	3,360465116	7	5	4	2	37,89
voiture	vwatyR	car	N	4,917647059	4,837209302	3,360465116	7	7	6	2	388,87
vol	vOl	flight	N	3,651162791	3,488372093	2,848837209	3	3	3	1	74,14
voyelle	vwajEl	vowel	N	3,662790698	4,209302326	3,255813953	7	5	5	2	0,36

Is RI domain-general or domain-specific? An aging study.

Coline Grégoire, Steve Majerus

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Abstract. The question of domain-specificity versus domain-generality of cognitive control is an essential but highly debated theoretical issue, with few empirical studies addressing this question directly. The present study investigated the effect of aging on resistance-to-interference (RI) capacity across three different domains (phonological, semantic, and visual) and for two different tasks. For both tasks, we observed a general age effect on RI abilities that did not reliably interact with domain. Correlational analysis overwhelmingly supported evidence for an absence of both within-domain and between-domain associations of RI abilities. Overall, the results support a view in which RI processes are highly specific. We argue that the cross-domain age effect on RI abilities alone cannot be taken as evidence for domain-general RI abilities and propose a neurocognitive task-specific account of RI abilities that is compatible with general age effects on RI.

Keywords. Resistance-to-interference; Aging; Domain-general; Domain-specific

Public Significance Statement. The research presented in this study holds significant implications for our understanding of cognitive aging and cognitive control. By examining resistance-to-interference abilities in young and older adults across different cognitive domains, our study challenges the prevailing assumption of domain-general cognitive control processes. Our findings furthermore call for targeted intervention strategies of cognitive decline in older individuals, as they emphasize the task- and domain-specificity of cognitive control and underlying resistance-to-interference abilities.

Open science statement

All stimulus materials and data set are available in a repository at the following address: https://osf.io/x4eha/.

Acknowledgments

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Conflict of interest

There is no conflict of interest in connection with this work.

Ethical statement

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by local ethics committee (Comité d'Ethique Hospitalo-Facultaire Universitaire de Liège; file number: B707201939419).

Fundings

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Introduction

Among cognitive control processes, Resistance-to-interference (RI) is commonly defined as the ability to selectively attend to relevant information while inhibiting the processing of irrelevant information (Dempster & Corkill, 1999). Although different subtypes of RI have been defined, the central versus domain-specific (e.g., verbal vs. visual) nature of these processes remains (Grégoire & Majerus, 2023). While some researchers have suggested that RI reflects a common capacity across different domains, such as verbal and visual domains (Delaney-Busch et al., 2016; Freitas et al., 2007; Kan et al., 2013; T. Wu et al., 2020) others have proposed that RI abilities are domain-specific or are applied in a domain-specific manner (Braem et al., 2014; Dempster, 1993; Egner, 2008; C. Kim et al., 2012; McCall et al., 2022; Schouppe et al., 2014; Verbeke & Verguts, 2021; G. Yang et al., 2017). The present study examines the question of the domain-generality of RI, by investigating the effect of aging on RI capacity across three different domains (phonological, semantic, and visual) and for two different tasks.

Domain-Specificity versus Domain-General Resistance-to-Interference.

While different subtypes of RI have been identified in the past (e.g., proactive interference, Postman, 1961; Postman & Underwood, 1973; Underwood & Ekstrand, 1966; reactive interference, McGeoch, 1932; McGeoch & Underwood, 1943; Melton & Irwin, 1940), few studies have explicitly addressed the question of the domain-generality of these RI processes. One of the few theoretical frameworks making an explicit distinction has been developed by Dempster (1993). The author proposed a taxonomy distinguishing perceptual RI (i.e., resisting to irrelevant auditory or visual stimuli like sounds or symbols), linguistic RI (i.e., resisting to irrelevant linguistic units such as words or sentences) and motor RI (i.e., resisting to push on a not / no more relevant response). Evidence in favour or against these assumptions is scarce and ambiguous.

At the behavioral level, Morey and Mall (2012) compared the performance of participants on working memory tasks for verbal or spatial stimuli by contrasting cued vs. interference-prone uncued dual-task conditions, finding a moderate correlation between verbal and spatial recall measures in uncued conditions but not in cued conditions. On the other hand, Oberauer et al. (2004) used a similar dual-task working memory paradigm to investigate RI capacity across domains, finding no support for domain-general RI processes. Sulpizio et al. (2022) examined RI capacity in verbal semantic and visual tasks, finding a small-to-moderate size correlation between verbal RI measures based on verbal lexical decision and Stroop tasks, but no significant correlation between RI measures for the visual Simon and the verbal lexical decision tasks, or between the verbal Stroop and the visual Simon tasks, supporting the existence of domain-specific rather than domain-general RI processes. Overall, there are very few studies directly comparing the capacity for RI across verbal and visual domains. It should be noted that many other studies have investigated between-domain RI effects , by examining for example whether verbal stimuli interfere with visual stimuli in RI tasks (Bird et al., 2000; Cowan & Barron, 1987; Cowan & Morey, 2007; Donohue et al., 2013; Driver & Baylis, 1993; Elliott et al., 1998, 2014; Guerreiro et al., 2013b; Hanauer & Brooks, 2005; Hazeltine & Wifall, 2011; Hirst et al., 2019; Ikeda et al., 2010; Miles et al., 1989; Redding & Gerjets, 1977; Roelofs, 2005; Tipper et al., 1988). The results from these studies are however difficult to interpret regarding the question of the domain-generality of RI processes given that the mere observation of cross-domain interference effects is more informative about the interference potential of specific stimuli in a specific task context than about the domain-specificity of capacity to resist interference.

A few neuropsychological studies have examined the question of selective RI deficits as a function of domain, and this mainly in patients with aphasia. A number of these studies suggested a dissociation between verbal and visual RI abilities, with impairment of verbal RI but preservation of visual RI abilities (Hamilton & Martin, 2005; Kuzmina & Weekes, 2017; R. C. Martin & He, 2004; R. C. Martin & Lesch, 1996). Some single case studies further examined dissociations for RI of phonological vs. semantic information within the verbal domain and showed that semantic RI can be specifically impaired in patients with verbal control deficits (Barde et al., 2010; Freedman & Martin, 2001; R. C. Martin & He, 2004; R. C. Martin & Lesch, 1996; McCall et al., 2022). However, robust double dissociations are still missing as the situation of preserved semantic RI, but impaired visual RI has not been reported so far (Hamilton & Martin, 2005; Kuzmina & Weekes, 2017). Neuropsychological evidence, while tending towards a domain-specific rather than a domain-general perspective of RI, remains limited.

A different strand of studies has investigated the neural correlates associated with RI, by distinguishing visual vs. verbal, and sometimes also phonological vs. semantic domains. While a number of studies showed the general recruitment of dorsolateral prefrontal cortex in both verbal and visual RI tasks (Funahashi, 2022; Kadota et al., 2010; S. Martin et al., 2006; Nathaniel-James, 2002), more subtle differences have also been reported, with a left-right hemisphere distinction. The right inferior frontal gyrus has been identified to be more specifically associated with visual RI tasks while the left inferior frontal gyrus has been associated with verbal RI, although it should be noted that the tasks used are not always structurally equivalent for the two stimulus domains (Morimoto et al., 2008; Schumacher et al., 2011; Stephan et al., 2003). A more limited number of studies has also obtained evidence for a possible specialization of the left inferior frontal gyrus as a function of semantic vs phonological RI, with the ventral anterior part being more specifically associated with semantic RI as opposed to the posterior dorsal part (Gold et al., 2005; Klaus & Hartwigsen, 2019; Poldrack et al., 1999; Snyder et al., 2007). Note however that a meta-analysis showed that that the anterior left inferior frontal gyrus could be involved in both phonological and semantic tasks, although the studies included did not necessarily directly contrast phonological vs. semantic RI (Liakakis et al., 2011).

RI and Aging

The present study will acquire novel evidence regarding domain-general vs. domain-specific hypotheses of RI by examining the way and extent RI is impacted across domains by the effect of cognitive aging. RI has been frequently associated with age-related deficits (Collette, Schmidt, et al., 2009; Collette & Salmon, 2014; Hasher & Zacks, 1988) in a large number of paradigms such as in the Stroop task (Augustinova et al., 2018; Jackson & Balota, 2013), in negative priming tasks (Tipper, 1991), in pro- and anti- saccade tasks (L. A. Abel & Douglas, 2007; Noiret et al., 2017), or in the Go/No-Go task (Rodríguez-Villagra et al., 2013). A recent meta-analysis however concluded that there appears to be no general age-related decline in RI (Rey-Mermet & Gade, 2018). In order to achieve a better understanding of age-related effects on RI, the authors called for a more controlled assessment of RI by designing paradigms that compare different constructs, functions, and, importantly, domains. At a neuroanatomical level, neural regions associated with RI are known to show age-related alterations (Hedden & Gabrieli, 2004; Raz, 2000; Raz et al., 1997; Raz & Rodrigue, 2006). Progressive prefrontal atrophy is among the most early age-related alteration known to induce also cognitive alterations, especially in tasks involving RI (Angel et al., 2010; Calso et al., 2016; Chao & Knight, 1997; Collette et al., 2005; Collette, Germain, et al., 2009; Collette, Schmidt, et al., 2009; McDonough et al., 2022; Paxton et al., 2008; West, 1996). These studies generally show reduced activity in the PFC when engaging in tasks that require RI, suggesting a lesser recruitment of the neural resources needed to perform these tasks (Yao & Hsieh, 2021).

Some studies have investigated more specifically the impact of aging on RI in visual or verbal domains. In terms of visual RI, some studies have suggested that older adults may be less able to filter out irrelevant visual information than younger adults, leading to increased interference and reduced performance on visual tasks (Noiret et al., 2017; Peltsch et al., 2011; Schik et al., 2000). Other studies have found that older adults are able to perform as well as younger adults on specific visual tasks that require RI (Kramer et al., 1994; Rey-Mermet & Gade, 2018). Similarly, in the verbal domain, some studies have found that older adults may be more susceptible to interference from irrelevant verbal information than younger adults (Hedden & Park, 2001, 2003) while other studies have found no age-related differences in verbal resistance to interference (Verhaeghen & De Meersman, 1998b, 1998a). Guerreiro et al. (2010) compared unimodal (e.g., visual task - visual interference) and transmodal (e.g., visual task - auditory interference) tasks. They observed elderly people to be more sensitive to visual interference whether the task was unimodal or transmodal (see also Guerreiro et al., 2013). However, while showing that elderly people may be more sensitive to visual than verbal interfering information, this does not yet show that RI is domain-specific as no direct comparison was made between interindividual differences for verbal vs. visual RI capacities.

The Present Study

This study investigates the question of domain-specific vs. domain-general RI abilities by examining the impact of aging on RI in the phonological, the semantic and the visual domains, by furthermore using two different tasks to rule out task-specific effects. We contrast in this study RI for verbal versus visual domains as these are the most frequently studied domains for research on RI. Furthermore, within, the verbal domain, we distinguish phonological vs. semantic aspects of the verbal information given emerging neuropsychological and neuroimaging evidence for a possible separation of RI abilities according to these two verbal sub-domains, as discussed earlier.

At the task-level, two tasks commonly used to measure RI were included in this study. A first task was a judgment task with variable interference buildup. This task has been commonly used in the verbal domain for assessing RI to irrelevant information mostly at the semantic level (Schnur et al., 2009; Thompson-Schill et al., 1997) with a recent adaptation to phonological RI (Attout et al., 2022). The task involves judging which of two test-items is the closest to two target-items, the presentation of the target-items being preceded by a prime stimulus that pre-actives a specific semantic, phonological, or visual information. In the RI condition, the pre-actived information interferes with the selection of the correct test-item as it primes the incorrect test-item. In the facilitation condition, it primes the correct test-item. The second task assessed RI in a working memory context to determine the extent to which the results observed for a direct stimulus-matching task can be extended to a task where RI relates to stimuli held in memory. We selected a recent-negative (RN) paradigm used in previous studies for assessing RI for both phonological and semantic aspects of memoranda (Hamilton & Martin, 2005, 2007). In this task, a sequence of to-be-memorized stimuli is presented, followed by a neutral negative probe item or a probe item that is similar to an item from the current or a previous memory list. Similar items will interfere with the probe-word and need to be rejected to lead to the correct response decision. We adapted the two tasks to allow for interference at phonological, semantic, and visual levels by using either nonwords, familiar words or difficult-to-verbalize complex visual figures. For the two tasks, the cost of RI was calculated by subtracting the average performance (response time, correct responses) on the "neutral” or “facilitation" trials from performance on the RI trials and divided it by the "neutral” or “facilitation” , and this separately for the phonological, semantic, and visual trials. We determined whether age effects on the RI measure interacted with stimulus domain, and this separately for the two tasks. Critically, we determined whether RI abilities for one domain/task predicted RI in another domain/task, via correlational analyses.

Method

Transparency and Openness

The study materials, the de-identified data set described in the Results section, and the Supplementary Data are available on the following open repository: https://osf.io/x4eha/ (Grégoire & Majerus, 2023). The study design, hypothesis and analytic plan were not preregistered. As analyses were performed with JASP, there is no raw R or SPSS code to provide. Any software (including versions numbers) has been displayed appropriately. We report how we determined our sample size, any data exclusions, all manipulations, and all measures in this study.

Participants

The current experiment was conducted at the Psychology & Neuroscience of Cognition Research Unit (PsyNCog) located at the University of Liège, Belgium from November 2019 to March 2020. Participants were recruited through advertisements on the university campus, via online platforms and by word-of-mouth. Sample size was estimated based on simulations using the BayesFactor package for R (Brysbaert, 2019; R. D. Morey et al., 2015). These simulations showed that a sample size of 110 participants per group provides a power of .86 for the interaction in a mixed 2 × 2 ANOVA design, for a $BF_{10} > 3$ and a $d = 0.5$. In order to compensate for participant drop out between sessions, we recruited 5 additional participants per group. Some participants ($n = 20$) had to be excluded because they failed to follow the instructions, or because there were missing data due to technical problems or participants not being available anymore (due to the Covid-19 sanitary situation). The final sample was composed of 111 young adult participants aged 20 to 40 years (Female: N = 52; Male: N = 59) and 99 elderly adult participants aged 60 to 80 years (Female: N = 49; Male: N = 50). All participants were French speakers and reported to have a corrected-to-normal vision and audition. None of the participants was taking any medication that could influence their cognitive functioning at the time of the test. Bayesian T-tests showed that the two groups were matched for level of education, but, as in most aging studies, had higher receptive vocabulary knowledge (see Table 1). Those were confirmed by Bayesian Informative Hypotheses Evaluation Welch T-Test (Hoijtink, Gu, et al., 2019; Hoijtink, Mulder, et al., 2019; Rodríguez-Villagra et al., 2013). All the elderly participants included in the study had a Montréal Cognitive Assessment score greater than or equal to 23 (Carson et al., 2018; Nasreddine et al., 2005), confirming an age-appropriate general cognitive status (M = 26.64, SD = 1.84, SE = 0.18, IC95 = [26.27, 27.00]). The study had been approved by the local ethics committee (Comité d'Ethique Hospitalo-Facultaire Universitaire de Liège; file number: B707201939419) in accordance with the principles of the Declaration of Helsinki.

Table 1

Participant characteristics (mean, standard errors, standard deviation, and credible intervals at 95%)

	Groups	**N**	**Mean**	**SE**	**SD**	**IC 95 lower**	**IC 95 upper**	**Bayesian T-Test**	**BAIN Welch T-Test**
Level of education	Young adults	111	13.91	0.15	1.58	13.62	14.20	$BF_{10} = 1.41$ ($BF_{01} = 0.71$)	$BF_{10} = 0.70$ ($BF_{01} = 1.43$)
	Elderly adults	99	13.32	0.23	2.27	12.88	13.77		

	Groups	N	Mean	SE	SD	IC 95 lower	IC 95 upper	Bayesian T-Test	BAIN Welch T-Test
Age	Young adults	111	23.32	0.39	4.16	22.55	24.10	BF_{10} = 58.01+127	$BF_{10} = \infty$
	Elderly adults	99	67.49	0.65	6.51	66.21	68.78		
Vocabulary level	Young adults	111	21.80	0.42	4.39	20.99	22.62	BF_{10} = 3317.96	BF_{10} = 3101.41
	Elderly adults	99	25.15	0.59	5.89	23.99	26.31		

Similarity-Judgment Task

Material

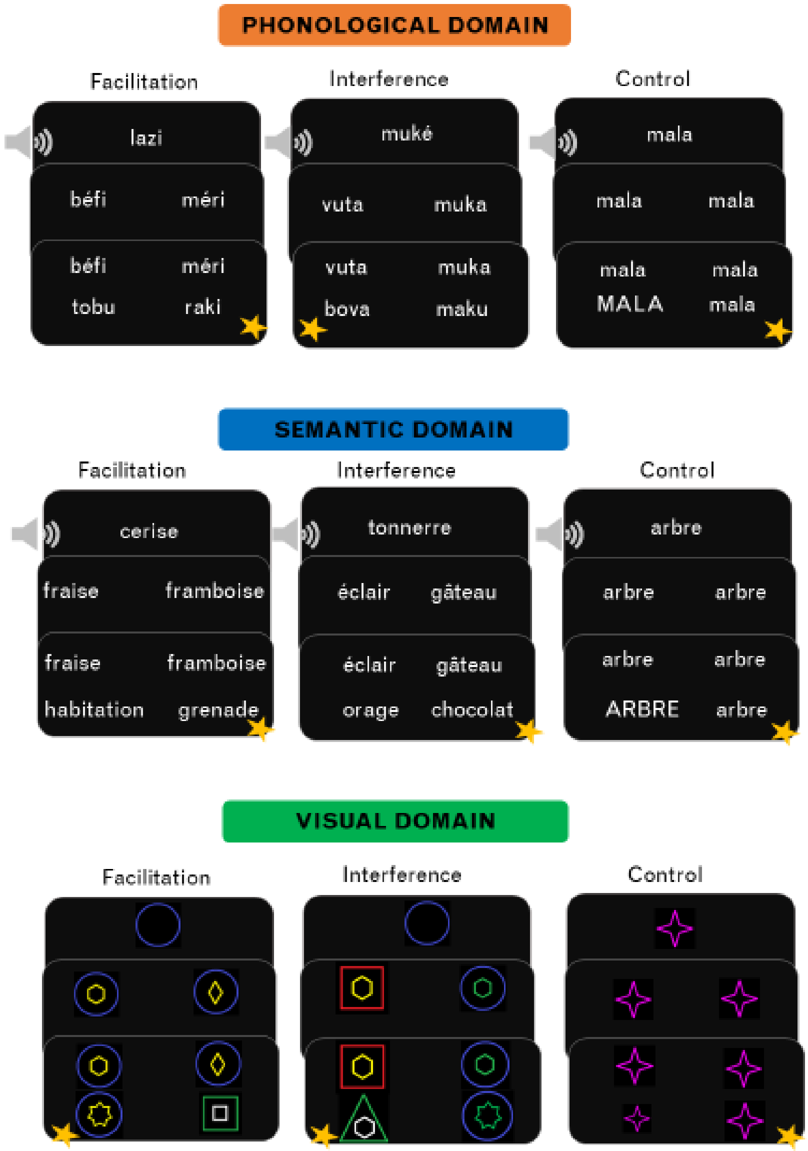
Phonological domain. The phonological similarity-judgment task required participants to match nonwords on a specific criterion. Participants were asked to choose the test nonword that was most close to both target nonwords, i.e., sharing a vowel in the same position. In the RI condition, the prime nonword, via its phonological similarity, pre-activated the wrong test nonwords. For example, for the target nonwords "vuta" and "muka", and the test nonwords “maku” and “bova”, the correct test nonword is “bova”, but the prime “muké” will pre-activate “muka” which then needs to be inhibited to allow for the correct test nonword to be chosen. In the facilitation condition, the prime nonword “lona” directly pre-activates the correct test nonword. A control condition that involved font matching judgments was also included to control for perceptual and motor aspects (see Figure 1). The prime nonwords were recorded by a female voice for auditory presentation, in order to maximally ensure. The nonwords were selected from a pool of 63 consonant-vowel-consonant-vowel-nonwords, based on Attout et al. (2022).

Semantic domain. The semantic similarity-judgment task used exactly the same structure as for the phonological task, except that words were presented, and the test words had to be selected based on semantic similarity with both target words. In the RI condition, the prime word, via its semantic similarity, pre-activated the wrong test word. For example, for the target words "éclair - a French desert but having also the thunder-related meaning of electric strike” and “gâteau – cake” and the test words “orage - thunderstorm” and “chocolat - chocolate”, the correct test word is “chocolat”, but the prime “tonnerre - thunder” will pre-activate “orage” which then needs to be inhibited to allow for the correct test word to be chosen. In the facilitation condition, the prime nonword “glace - ice cream” would directly pre-activate the correct test nonword (see also Figure 1 for further examples). We selected 118 words controlled for concreteness, imageability, frequency, number of letters and syllables, number of phonological and orthographic neighbours, and orthographic and phonological uniqueness points values matched between the facilitation and interference lists (BF_{10} = [0.21 to 1.10], BF_{01} = [0.91 to 4.83], Bayesian Independent Samples T-test and descriptive data available in the Supplementary Material file. Psycholinguistics variables were extracted from Lexique database (New et al., 2001, 2004) while concreteness and imageability were taken from a database presented in Grégoire et al. (*in press*).

Visual domain. The visual similarity-judgment task followed the same structure as the two other tasks, except that colored geometric shapes were presented and the test stimuli had to be selected based on maximal visual similarity with both target stimuli (see Figure 1). Participants were asked to choose the test-symbol that had at least one common element with the two target-items, which were composed of internal and external geometric coloured shapes. For example, in the RI condition shown in Figure 1, the prime stimulus pre-activated the test stimulus with blue external circle but this aspect was only shared with one of the two target stimuli; the correct answer was the test-stimulus with an internal hexagon as it was the element shared with both target items. In the facilitation condition depicted in Figure 1, the shape (○) and colour (blue) of the prime-stimulus were identical to both target items and to the correct answer, facilitating correct response selection. A control condition was also included to control for perceptual and motor aspects, where the same shape appeared for each stimulus type, with only the size differing between the target and test words. Participants had to select the test symbol presented in the same size as both target words. Visual stimuli were constructed from six geometric shapes (circle, heptagram, hexagon, diamond, square, triangle) and five colors (white, red, blue, yellow, green).

Figure 1

Illustration of the phonological, semantic, and visual similarity-judgement tasks, for facilitation, interfering, and control conditions.



Note. Yellow stars indicate the correct response.

Procedure

The phonological, semantic, and visual and visual Similarity-Judgment Task were administered in separate blocks. The auditory or visual prime stimuli were presented for 2000 ms, followed by the two target-stimuli on the upper part of the screen, and 2000 ms later, in addition the two test-stimuli on the lower part of the screen. Participants had to select the correct testitem within 4000 ms by pushing the "Z" key for selecting the test-stimulus on the left, or the "O" key for selecting the test-stimulus on the right (French AZERTY keyboard) (see Figure 1). For each task, there were 26 facilitation trials, 26 RI trials and 10 control trials. Right and left correct responses had the same probability. The three domain conditions were presented in the same session, with domain block order randomized between participants. For each domain, there were 10 practice trials. The task was presented via OpenSesame software version 3.3.5 (Mathôt et al., 2012). Both response accuracy and response times were collected. We calculated interference scores as follows: ((facilitation-interference)/facilitation).

Recent-Negative Task

Material

Phonological domain. The phonological recent-negative task consisted of the auditory presentation of four nonwords to be maintained and a test nonword (Figure 2). Volunteers had to judge whether the test nonword had been in the just presented list or not. The lists were sampled from 25 minimal phonological pairs (e.g., peussu /*pøsy*/ – feussu /*føsy*/) with only one item of each pair being selected for inclusion in a specific memory list.

Semantic domain. The semantic recent-negative task was built with the exact same design. The only difference was that participants were presented with 6 items as a pre-test study had shown a ceiling effect for 4-item word memory lists. The lists were sampled from 25 pairs of semantically related words (e.g., dog-cat). Semantic relatedness ratings had been obtained from the database provided by Ferrand and Alario (1998). Only one item of each pair was selected for inclusion in a specific memory list. Psycholinguistics variables were extracted from Lexique database (New et al., 2001, 2004) while concreteness and imageability were taken from a previous paper (Grégoire et al., *submitted*). Pairs were therefore controlled with concreteness, imageability, frequency, number of letters, number of phonological and orthographic neighbours, and orthographic and phonological uniqueness points (BF_{10} = [0.21 to 2.26], BF_{01} = [0.44 to 2.89], Bayesian

Independent Samples T-test and descriptive data available in the Supplementary Material file).

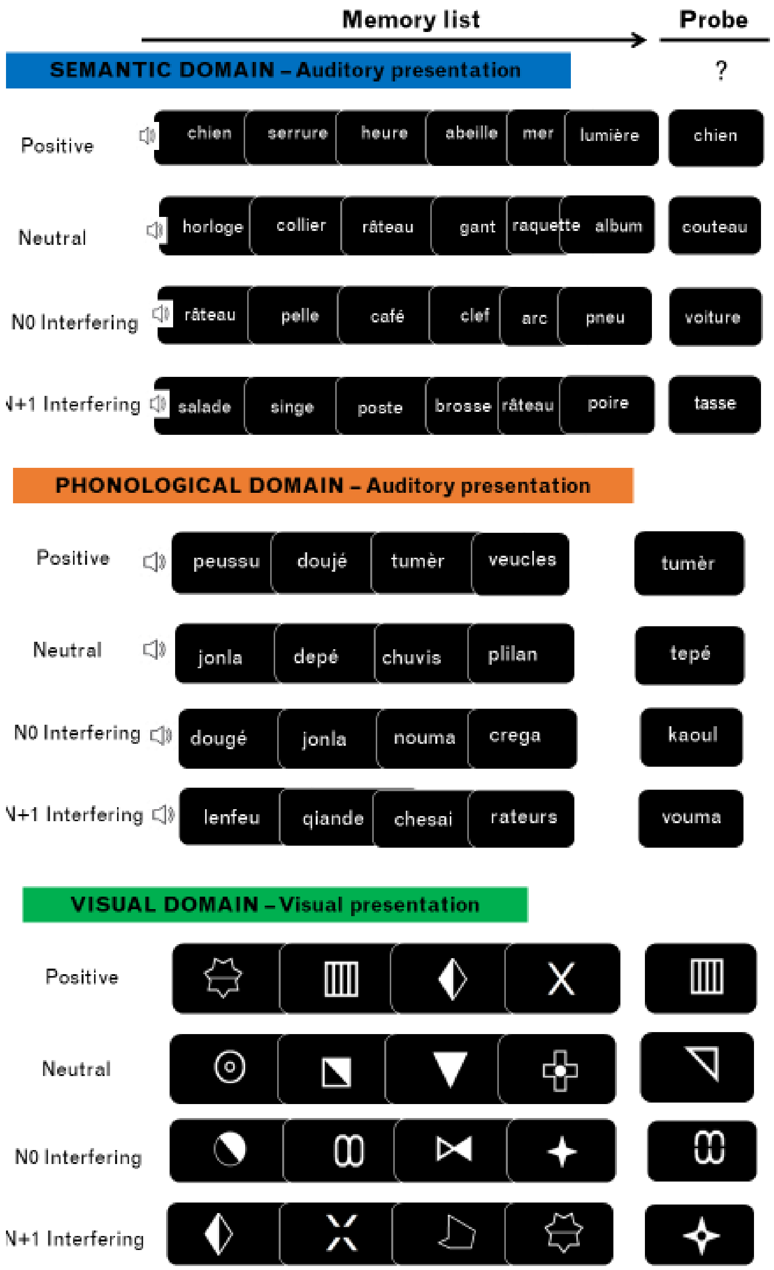
Visual domain. The visual recent-negative task consisted of the visual presentation of four visual shapes to be memorized and a test shape (Figure 2). The material was composed of 25 pairs of visually similar shapes, based on one out of five visual dimensions: "rounds" (e.g., ◎ - ◉), "squares" (e.g., ◪ - ◩), "triangles" (e.g., ▽ -△), "crosses" (e.g., ✚ - ✜), and "other shapes" (e.g., ⬡ - ⬠). We ensured that no symbol from the same category was taken twice except for inclusion in a specific memory list. A full list of materials is given in the Supplementary Material file.

Procedure

For each of the three tasks, the memory stimuli were presented at the rate of 2000 ms per stimulus. After a 1500 ms delay after the final memory stimulus, a probe stimulus was presented followed by an interrogation mark. The participants were asked to decide as quickly as possible whether the probe stimulus matched one of the stimuli in the list. The participants responded by either pushing the “L” key for “Yes, it was in the list” or by pushing the “S” key for “No, it was not in the list” (French AZERTY Keyboard). For each task domain, there were 4 conditions: 20 positive trials (the probe is identical one of the stimuli of the current memory list), 20 negative trials with the probe being close to one of the stimulus from the list (N0 interference trials), 20 negative trials with the probe being close to one of the stimulus from the previous list (N+1 interference trials) and 20 neutral negative trials (no similarity with one of the memory stimuli). For each domain, there were 8 practice trials. For the phonological and visual tasks, each nonword or shape occurred 8 times across the different trials. For the semantic task, each word was presented 11 or 12 times. The different stimulus occurrences were distributed as evenly as possible over the different serial positions, with pseudo-random order of the trials. Accuracy (percentage of correct responses), response times (for correct responses) and an interference score ((neutral – interfering N+1)/neutral) were measured. For this measure, the N+1 scores were used as they were considered to be most sensitive to interference processes. N0 trials reflect both interference and within-list working memory decay processes and thus may be considered a less direct measure of interference processes.

Figure 2

Illustration of the phonological, semantic, and visual Recent-Negative Task with positive, neutral, N0 interfering, and N+1 interfering conditions.



Additional assessment

Speed Processing. The X-O letter comparison test (Salthouse, 1990) was used to control for processing speed differences in the young and elderly groups. Participants were given a sheet of paper with pairs of letters (XX, OO, XO, or OX). When these two letters were identical, they must tick the "identical" box, while when they were different, they had to tick the "different" box. Participants were asked to tick the boxes as fast as possible within a time limit of 30 seconds. One point was awarded for each correct comparison, the higher the score, the higher processing speed This measure was introduced as a covariate for analyses on reaction times.

General procedure

The different tasks described above were presented in two different sessions. Consent and demographic data forms were presented at the first session. The Similarity-Judgement task and the Recent-Negative task and their submodalities were presented in different sessions in a counterbalanced manner. Phonological, semantic, and visual modalities (i = 3) were presented in different blocks counterbalanced within each session (j = 2), for each task (k = 2). Therefore, we obtained twelve counterbalanced conditions ($i \times j \times k$ = 12). Half of the participants were presented with the vocabulary test (i.e., Mill-Hill) on the first session while the other half fulfilled it during the second session. The same applied for the speed processing test (i.e., XO). There was a mean interval of 3.13 days between both sessions without any difference between young (M = 3.41, SE = 0.34, IC95 = [2.72, 4.10]) and elderly adults (M = 2.89, SE = 0.25, IC95 [2.40, 3.40]), BF_{10} = 0.28; BF_{10} = 3.53. Each session was one-hour long. To ensure that participants were hearing items appropriately even when semantic and/or phonological items were close, we presented them a computerized small list of words (e.g., recherche (*research)*, flou *(blurry)*, amande (*almond)*, sensation (*sensation*), tentation (*tentation*), ville (*city*), papier (*paper*), panier (*bucket*), congés (*vacations*), vacances (*holidays*), chaire (*chair*), chaine (*chain*)). Volume was set up at 50% from the computer capacity and adapted by adding/removing 10 volume points if the participants could not distinguish and clearly repeat the test-items. Each task including auditory items was displayed within headphones with the appropriate volume. The mean volume across all participants was around 50%.

Data Analysis, Bayesian Statistical Approach

A Bayesian statistical approach was used, in order to appreciate evidence both *in favor* and *against* our effects of interest while frequentist statistics only allow to interpret evidence in favor of these effects (Wagenmakers, 2007). Bayesian statistics also reduce Type-1 error probability (Schönbrodt et al., 2017). Bayesian analyses compute evidence against or in favor of a given model along a continuous dimension (the Bayes factor values - BF), rather than deciding for the presence of an effect based on an arbitrary statistical threshold (Schönbrodt & Wagenmakers, 2018). The BF_{10} value represents the likelihood ratio of the alternative model (H_1) relative to the null model (H_0); the likelihood ratio of H_0 relative to H_1 corresponds to the reverse, $BF_{01} = 1/BF_{10}$. The following classification of strength of evidence was used (Jeffreys, 1961; Lee & Wagenmakers, 2014): A BF of 1 provides no evidence, 3 > BF > 1 provides anecdotal evidence, 10 > BF > 3 provides moderate evidence, 30 > BF > 10 provides strong evidence, 100 > BF > 30 provides very strong evidence, and BF > 100 provides extreme/decisive evidence. Bayesian analyses were conducted with Version 0.16.3 of the JASP software package (JASP Team, 2022, jasp-stats.org) and included random slopes for repeated-measures interaction (Bergh et al., 2022). Default prior parameters were used (r scale of the Cauchy distribution for t-tests was set to .707; the r scale was set to .5, 1, .354, for ANOVA fixed effect, random effects, and covariates, respectively. Bayesian post-hoc tests were performed with Bayesian Paired and Independent Sample T-Tests. Note that for each Bayesian ANOVA performed, descriptive data (including mean, standard deviations, standard errors, and credible intervals at 95%) and full model comparison tables are presented in the Supplementary Data file.

Results

Accuracy and Response Times

Similarity-Judgment Task

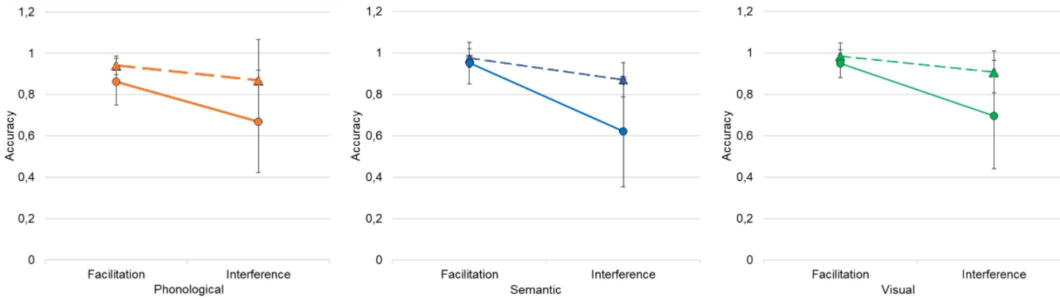
A first 2 (Groups: Young adults, Elderly adults) x 2 (Conditions: Facilitation, Interference) x 3 (Domains: Phonological, Semantic, Visual) Bayesian Repeated Measures ANOVA was performed on the overall accuracy score. Results are displayed in Figure 3. The model associated with the strongest evidence (BF_{10} = 1.88+76) included the three main factors (Groups: $\eta^2_p = .39$, Domains: $\eta^2_p = .06$, Conditions: $\eta^2_p = .64$), the interaction between Domains and Conditions ($\eta^2_p = .06$) as well as the interaction between Conditions and Groups ($\eta^2_p = .32$). This model was 9.09 more likely than the second one that included the same factors as well as the interaction between Domains and Groups and the triple interaction between Domains, Conditions and Groups (see Supplementary Data file). An Independent

Samples T-Test showed that accuracy was higher for the younger group compared to the elderly group (BF_{10} = 3.44+20). Bayesian Paired Samples T-Tests also revealed a better accuracy in the Facilitation conditions compared to the Interference conditions (BF_{10} = 5.03+33). Accuracy was also higher in the Visual domain compared to the Phonological (BF_{10} = 5205.68) and Semantic domains (BF_{10} = 8.51) but there was no reliable evidence for a difference between Phonological and Semantic domains ($BF_{10} < 1$, BF_{01} = 1.16). The interaction between Domains and Conditions indicates that the interference effect was particularly pronounced in the semantic task domain (Phonological: η^2_p = .27; Semantic: η^2_p = .50; Visual: η^2_p = .38). The interaction between Conditions and Groups indicates that the elderly group showed overall stronger interference effects in all task domains, relative to the young adult group (Elderly adults: η^2_p = .71; Young adults: .51).

Another 2 (Groups: Young adults, Elderly adults) x 2 (Conditions: Facilitation, Interference) x 3 (Domains: Phonological, Semantic, Visual) Bayesian Repeated Measures ANOVA was performed on the response times for correct answers, with processing speed as a covariate. Results are displayed in Figure 4. The most parsimonious model with the strongest evidence (BF_{10} = 5.77+147) included the three main factors (Groups: η^2p = .22, Domains: η^2p = .02, Conditions: η^2p = .04), the covariate (η^2p = .18), the interactions between Domains and Conditions (η^2p = .06), and Conditions and Groups (η^2p = .12), see Table in Supplementary Data. Post-hoc tests showed that the younger adult group was faster to respond compared to the elderly group (BF_{10} = 8.61+29). The post-hoc tests also revealed that responses were faster in the Facilitation conditions compared to the Interference conditions (BF_{10} = 2.45+46), and in the Visual domain compared to the Phonological (BF_{10} = 1.65+40) and Semantic domains (3.25+13), as well as in the Semantic domain compared to the Phonological domain (BF_{10} = 5.39+20). The interaction between Domains and Conditions indicates that the interference effect was overall more pronounced in the visual task domain relative to the semantic and phonological task domains (Phonological: η^2p =.05; Semantic: η^2p = .07; Visual: η^2p = .23). The interaction between Groups and Conditions indicates that the elderly group showed overall stronger interference effects relative to the young adult group (Young adults: η^2p = .10; Elderly adults: η^2p = .02). Note that these analyses take into account the effect of the processing speed covariate while Figure 4 presents raw descriptive results.

Figure 3

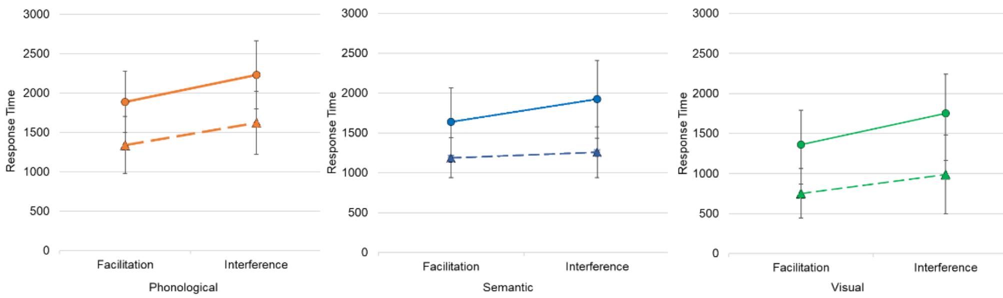
Plots for accuracy (correct responses) in terms of Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference) and Groups (Young adults, Elderly adults) for the Similarity-Judgment Task.



Note. Young adults' data are represented by doted lines and triangles --▲, and elderly adults' data are provided by plain lines and circles -●. Each mean is displayed with standard deviation.

Figure 4

Plots for Response Times in milliseconds (for correct responses) in terms of Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference) and Groups (Young adults, Elderly adults) for the Similarity-Judgement Task.



Note. Young adults' data are represented by doted lines and triangles --▲, and elderly adults' data are provided by plain lines and circles -●. Each mean is displayed with standard deviation.

Recent-Negative Task

A first 2 (Groups: Young adults, Elderly adults) x 3 (Conditions: Neutral, N0 Interfering, N+1 Interfering) x 3 (Domains: Phonological, Semantic, Visual) Bayesian Repeated Measures ANOVA was performed on the overall accuracy score of the Recent-Negative Task. Results are displayed in Figure 5. The model associated with the strongest evidence ($BF_{10} \rightarrow \infty$; $BF_M = 359.35$[5]) included the three main factors (Groups: $\eta^2_p = .26$, Domains: $\eta^2_p = .63$, Conditions: $\eta^2_p = .85$), the interaction between Domains and Conditions ($\eta^2_p = .62$) as well as the interaction between Groups and Domains ($\eta^2_p = .06$). This model was more likely than the second one ($BF_{10} \rightarrow \infty$; $BF_M = 0.89$) including the same variables plus the interaction between Groups and Conditions. Post-hoc tests showed that overall accuracy was higher for the young adult group compared to the elderly group (BF_{10} = 2.38+12). Participants also performed better in the neutral condition compared to the N0 interfering (BF_{10} = 8.10+98) and N+1 interfering (BF_{10} = 5.51+43) conditions, the latter leading also to higher performance than the N0 interfering condition (BF_{10} = 2.70+75). Regarding the domains, performance was overall higher in the visual domain compared to the semantic and phonological domains (BF_{10} = 7.70+15 and BF_{10} = 2.02+32), and better in the semantic domain relative to the phonological domain (BF_{10} = 3.02+63). The interaction between Domains and Conditions reveals stronger interference effects in the visual and phonological task relative to the semantic task (Phonological: η^2_p =.78; Semantic: $\eta^2_p = .09$; Visual: $\eta^2_p = .75$), and this particularly for N0 interfering probes. The interaction between Groups and Domains shows particularly decreased performance in the elderly group relative to the young adult group in the phonological task, the group effect being less pronounced in the other conditions (Group effect: Phonological: $\eta^2_p = .26$; Semantic: $\eta^2_p = .12$; Visual: $\eta^2_p = .10$).

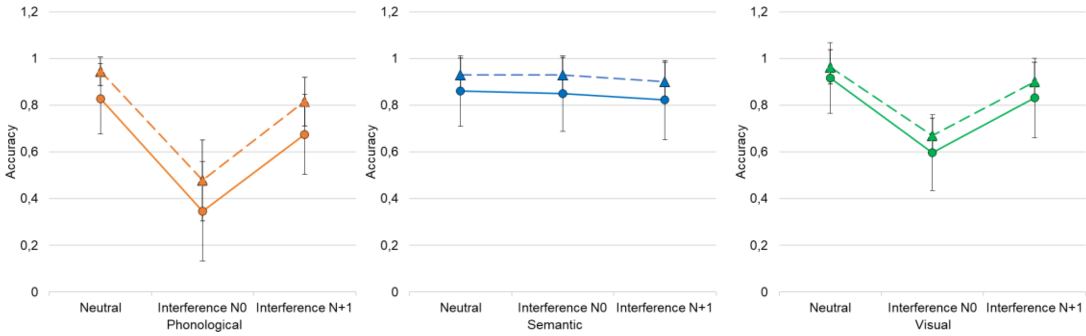
A second 2 (Groups: Young adults, Elderly) x 3 (Conditions: Neutral, Interfering N0, N+1 Interfering) x 3 (Domains: Phonological, Semantic, Visual) Bayesian Repeated Measures ANOVA was performed on the response times for correct answers. Results are displayed in Figure 6. The model associated with the strongest evidence (BF_{10} = 2.50+266) included the three main variables (Groups: η^2_p

5 The BF_M corresponds to the change from the prior odds to the posterior odds for the model. It represents the odds of a model after observing data and it is obtained by dividing the posterior odds by the prior odds (Courey et al., 2022). It is precise in this analysis as the two first models got very high $BF_{10} \rightarrow \infty$.

= .08, Domains: η^2_p = .08, Conditions: η^2_p = .02), the covariates (η^2_p = .14) and the interaction between Domains and Conditions (η^2_p = .1.31-3). This model was 25.43 more likely than the second one including the same variables as well as the interaction between Domains and Conditions (see Supplementary Data file). Post-hoc analyses showed that the younger adult group was faster to respond compared to the elderly group (BF_{10} = 1.28+16). Participants were also faster in the Neutral condition compared to the Negative N0 (BF_{10} = 1.88+51) and N+1 (BF_{10} = 1.58+27) conditions; they were also faster in the Negative N+1 condition compared to the N0 condition (BF_{10} = 2.03+24). Overall, participants answered faster in the visual trials compared to the semantic (BF_{10} = 8.27+73) and phonological (BF_{10} = 4.96+87) trials, which were also slower than the semantic trials (BF_{10} = 13143.05). Like for accuracy, the interaction between Domains and Conditions reveals stronger interference effects in the visual task relative to the semantic and phonological tasks, and this particularly for N0 interfering probes (Phonological: η^2_p = 8.74-3; Semantic: η^2_p = .01; Visual: η^2_p = .05).

Figure 5

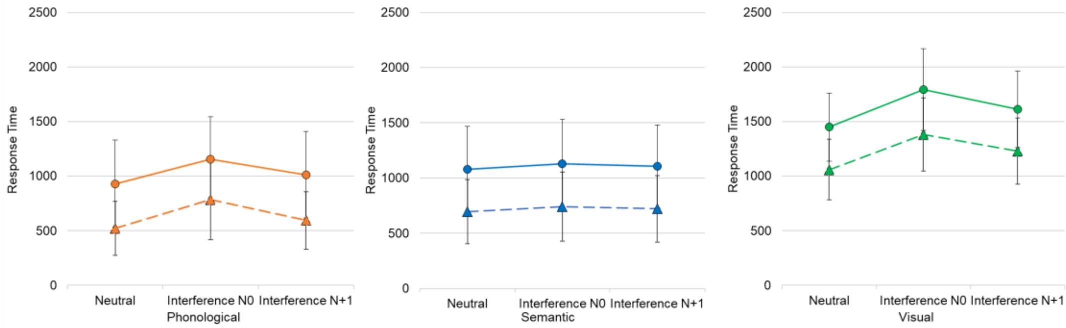
Plots for Accuracy in terms of Domains (Phonological, Semantic, Visual), Conditions (Neutral, N0 Interfering, N+1 Interfering) and Groups (Young adults, Elderly adults) for the Recent-Negative Task.



Note. Young adults' data are represented by doted lines and triangles --▲, and elderly adults' data are provided by plain lines and circles -●. Each mean is displayed with standard deviation.

Figure 6

Plot for Response Times in milliseconds (for correct responses) in terms of Domains (Phonological, Semantic, Visual), Conditions (Neutral, N0 Interfering, N+1 Interfering) and Groups (Young adults, Elderly adults) for the Recent-Negative Task.



Note. Young adults' data are represented by doted lines and triangles --▲, and elderly adults' data are provided by plain lines and circles -●. Each mean is displayed with standard deviation.

Between tasks: Accuracy and Response times Interference Scores

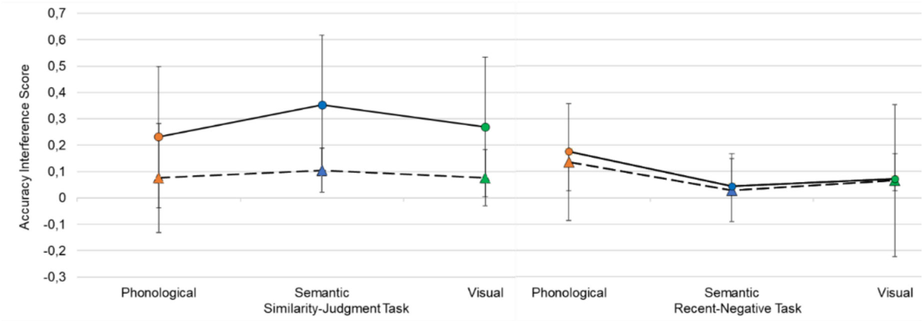
A next set of analyses directly compared interference scores across the two tasks (see Methods for calculation of the interference score). A first 2 (Groups: Young adults, Elderly adults) x 3 (Domains: Phonological, Semantic, Visual) x 2 (Tasks: Similarity-Judgement, Recent-Negative) Bayesian Repeated Measures ANOVA was performed on accuracy interference scores. Note that the higher the accuracy interference score, the greater the interference effect. Results are displayed in Figure 7. The model associated with the strongest evidence (BF_{10} = 4.53+40) included the three main variables (Groups: η^2_p = .26, Domains: η^2_p = .02, Tasks: η^2_p = .23) and the interactions between Domains and Tasks (η^2_p = .14) as well as the interaction between Tasks and Groups (η^2_p = .19). This model was 13.89 more likely than the second one including the same variables as well as the interaction between Domains and Groups. Overall, the elderly group showed increased interference scores relative to the young adult group (BF_{10} = 25787.93) as shown by post-hoc tests. Both groups were also more impacted in the similarity-judgement task compared to the recent-negative task (BF_{10} = 6.35+7). There was no difference in interference scores between the semantic and the visual (BF_{01} = 8.66) domains, and there was evidence for a difference between phonological domain and the visual (BF_{10} = 1.33+12) and semantic domains (BF_{10} = 2.30+12). The interaction between Domains and Tasks confirmed the results of the previous task-specific analyses, by showing stronger interference effects for the semantic versus phonological and visual similarity judgment task domains (Phonological: η^2_p = 9.57-5; Semantic: η^2_p = .39; Visual: η^2_p = .10). Finally, the interaction between Tasks and Groups suggests that interference effects were particularly pronounced in the elderly group versus the young adult group for the similarity-judgement task (Similarity-Judgement: η^2_p = .32; Recent-Negative: η^2_p = .7.00-3), see Figure 7.

The same analysis was conducted on response times. Note that for response times interference scores, a higher score means that a participant was less prone to interference. A 2 (Groups: Young adults, Elderly adults) x 3 (Domains: Phonological, Semantic, Visual) x 2 (Tasks: Recent-Negative, Similarity-Judgement) Bayesian Repeated Measures ANOVA showed that the model with the strongest evidence (BF_{10} = 2.72+30) included the three main factors (Groups: η^2_p = 1.16-4, Domains: η^2_p = .22, Tasks: η^2_p = .24), the interactions between Domains and Tasks (η^2_p = .03), Tasks and Groups (η^2_p = .05), and Domains and Groups (η^2_p =

.04). Results are displayed in Figure 8. This model was 3.19 more likely than the second one including the same variable as well as the triple interaction. Post-hoc tests showed that both groups showed less interference in the recent-negative task compared to the similarity-judgement task (BF_{10} = 9.82+9). Participants showed stronger interference in the visual domain compared to the semantic domains (BF_{10} = 9.27+19), and a greater interference in the phonological domain compared to the semantic domain (BF_{10} = 1.77+10) and visual domain (BF_{10} = 6.95). The interaction between Tasks and Domains is explained by a selectively less pronounced interference effect for the visual condition in the judgment task. (Effect of Domain: Similairty-Judgment: η^2_p = .17; Recent-Negative: η^2_p = .08). The interaction between Groups and Tasks is explained by particularly stronger interference effects in the elderly vs. young adult group for the similarity judgment task as compared to the recent negatives task (task effect: Young adults: η^2_p = .08; Elderly adults: η^2_p = .44). The interaction between Groups and Domains is explained by stronger interference effects in the elderly relative to the young adult participants mainly for the semantic domain (group effect: Phonological: η^2_p = .02; Semantic: η^2_p = .06; Visual: η^2_p = .5.33-3).

Figure 7

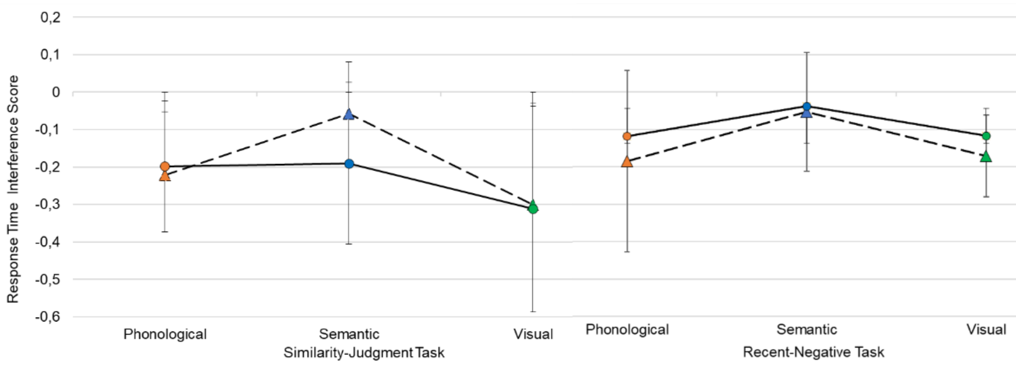
Accuracy Interference Scores in terms of Domains (Phonological, Semantic, Visual) and Groups (Young adults, Elderly adults) for the Similarity-Judgement Task (left panel) and the Recent-Negative (right panel) Task.



Note. Young adults' data are represented by doted lines and triangles --▲, and elderly adults' data are provided by plain lines and circles -●. Each mean is displayed with standard deviation.

Figure 8

Response Time Interference Scores in terms of Domains (Phonological, Semantic, Visual) and Groups (Young adults, Elderly adults) for the Similarity-Judgement Task (left panel) and the Recent-Negative (right panel) Task.



Note. Young adults' data are represented by doted lines and triangles --▲, and elderly adults' data are provided by plain lines and circles -●. Each mean is displayed with standard deviation.

Relationship Between Semantic, Phonological, and Visual RI

Next, we performed the critical between-task and between-domain correlation analyses to further examine the degree of domain-specificity of RI abilities and associated age effects. We correlated phonological, semantic, and visual accuracy and response time interference scores within in each group. This was done first separately for each task, and then across the two tasks. Results are displayed in Table 2 for the younger group, and in Table 3 for the elderly group.

Within Similarity-Judgment Task

No correlation was supported with decisive evidence in the younger group (all $BF_{10} < 3$; $BF_{01} = 0.94$ to 8.06). In the elderly group, correlations between phonological and semantic interference scores were associated with moderate evidence, for both accuracy interference scores ($r = .28$, $BF_{10} = 5.2$) and response times interference scores ($r = .36$, $BF_{10} = 79.97$). We further examined these associations with a Bayesian linear multiple regressions (using the JZS prior of 0.354, Jarosz & Wiley, 2014; Rouder et al., 2009) controlling for age and vocabulary level. When predicting the accuracy phonological interference score, the model providing the highest BF value was the model including both the semantic response times interference score and vocabulary level ($BF_{10} = 222.52$, $R^2 = .17$), and was 2.17 times more likely than the model with the next-highest BF which also included the age variable ($BF_{10} = 102.34$, $R^2 = .18$). The same pattern of results was observed when predicting the phonological accuracy interference scores by the semantic interference score and age ($BF_{10} = 25.07$, $R^2 = .13$ for the full model).

Within the Recent-Negative Task

Except for one correlation in the elderly adults between the phonological and visual accuracy interference scores ($r = .62$, $BF_{10} = 8.19+8$), all other correlations were associated with a $BF_{10} < 1$ ($BF_{01} = [1.22\text{-}9$ to $8.39]$). When predicting the phonological accuracy interference score using a regression model controlling for age and vocabulary level, the model associated with the highest evidence was a model including the visual interference score only ($BF_{10} = 1.67+9$, $R^2 = .39$).

Between-Task Correlation Analyses

To specify the relationship between the same domains from recent-negative and the judgement-similarity tasks, we correlated the accuracy and response times interference scores between the different modalities and tasks (Recent-Negative and

Similarity-Judgement). When examining within-domain correlations (e.g., correlations between phonological Similarity-Judgment and Recent-Negative tasks) for accuracy, BF values supported the absence of correlation in the young adult group (BF_{01} = [4.620; 7.587; 8.378] for phonological, semantic, and visual scores respectively) as well as in the elderly group (BF_{01} = [3.129; 5.741; 6.051]). The same was observed when correlating response time scores (BF_{01} = [1.979; 4.610; 8.161]) in the young adult group and in the elderly group (BF_{01} = [2.754; 3.090; 7.932]). Of the overall 60 correlation analyses, only five were associated with robust evidence for their presence, and these correlations were mainly limited to task-specific correlations in the elderly group.

Table 2

Bayesian Pearson Correlation Matrix between each interference score (accuracy scores: below the diagonal; response times scores: above the diagonal) for the Similarity-Judgment (SJ) and the Recent-Negative (RN) tasks for the young adults.

Variables		RN Visual	RN Phonological	RN Semantic	SJ Visual	SJ Phonological	SJ Semantic
RN Visual	Pearson's r	—	0.11	0.23	-0.03	-0.05	0.10
	BF_{10}	—	0.23 #	2.00	0.12 #	0.14 #	0.21 #
RN Phonological	Pearson's r	6.15-3	—	0.02	0.06	-0.11	0.10
	BF_{10}	0.12 #	—	0.12 #	0.15 #	0.22 #	0.21 #
RN Semantic	Pearson's r	0.09	0.01	—	-0.04	-0.03	-0.16
	BF_{10}	0.18 #	0.12 #	—	0.13 #	0.12 #	0.51
SJ Visual	Pearson's r	0.11	-3.151×10^{-4}	0.06	—	-0.03	0.20
	BF_{10}	0.22 #	0.12 #	0.12 #	—	0.12 #	1.06
SJ Phonological	Pearson's r	0.21	-0.01	0.05	0.23	—	0.14
	BF_{10}	1.27	0.12 #	0.14 #	2.50	—	0.37
SJ Semantic	Pearson's r	0.02	0.01	0.05	0.03	-0.01	—
	BF_{10}	0.12 #	0.12 #	0.13 #	0.13 #	0.12 #	—

Note. # flags correlations for which $BF_{01} > 3$, considered as positive evidence for an absence of correlation.

Table 3

Bayesian Pearson Correlation Matrix between each interference score (accuracy scores: below the diagonal; response times scores: above the diagonal) for the Similarity-Judgment (SJ) and the Recent-Negative (RN) tasks for the elderly adults.

Variables		RN Visual	RN Phonological	RN Semantic	SJ Visual	SJ Phonological	SJ Semantic
RN Visual	Pearson's r	—	-0.01	0.13	-0.13	0.05	0.20
	BF_{10}	—	0.13 #	0.28 #	0.27 #	0.14 #	0.95
RN Phonological	Pearson's r	**0.62**	—	0.19	0.22	-7.98-4	0.29
	BF_{10}	**8.19+8**	—	0.72	1.32	0.13 #	8.46
RN Semantic	Pearson's r	-0.16	0.14	—	-0.11	0.10	0.15
	BF_{10}	0.45	0.33 #	—	0.22 #	0.20 #	0.38
SJ Visual	Pearson's r	-0.08	0.02	0.08	—	0.01	0.05
	BF_{10}	0.17 #	0.13 #	0.17 #	—	0.13 #	0.14 #
SJ Phonological	Pearson's r	-0.07	0.07	0.08	0.16	—	**0.36**
	BF_{10}	0.16 #	0.16 #	0.17 #	0.43	—	**79.97**
SJ Semantic	Pearson's r	-0.09	7.15-3	0.15	**0.26**	**0.28**	—
	BF_{10}	0.19 #	0.13 #	0.38 #	**3.24**	**5.42**	—

Note. # flags correlations for which $BF_{01} > 3$, considered as positive evidence for an absence of correlation.

Discussion

Summary of the results

Table 4

Summary of the Effects Across the Different Tasks and Measures.

	Groups	Domains	Conditions (or Tasks)	Domains ✻ Conditions (or Tasks)	Groups ✻ Conditions (or Tasks)	Groups ✻ Domains	Groups ✻ Domains ✻ Conditions (or Tasks)
Similarity-Judgment: Accuracy	✓	✓	✓	✓	✓	BF_{01} = 24.48	BF_{01} = 7.61
Similarity-Judgment : Response Times	✓	✓	✓	✓	✓	BF_{01} = 1.43	BF_{01} = 2.55
Recent-Negative: Accuracy	✓	✓	✓	✓	BF_{01} = 12.43	✓	BF_{01} = 203.83
Recent-Negative: Response Times	✓	✓	✓	✓	BF_{01} = 3.31+46	BF_{01} = 39.59	BF_{01} = 55.95
Between-Tasks: Accuracy Interference Score	✓	✓	✓	✓	✓	BF_{01} = 13.40	BF_{01} = 1.05
Between-Tasks: Response Times Interference Score	✓	✓	✓	✓	✓	✓	BF_{01} = 3.66

This study investigated age effects on RI abilities, with the aim to determine the domain-specific versus domain-general nature of these effects. By using structurally identical tasks for measuring RI in phonological, semantic, and visual domains, we observed group, domain, and condition (RI) effects for response accuracy as well as for response times (see Table 4). Critically, only two out of the six Groups by Domains interactions (see Table 4) were supported with positive evidence whereas the other four were associated with anecdotal to strong evidence for an absence of interaction. Correlational analysis overwhelmingly supported evidence for an absence of both within-domain and between-domain associations of RI abilities.

On the one hand, we observed a general age effect, which, on first sight, appears to support a domain-general nature of RI and their age-related decline. As a reminder, domain-general theories propose that age-related cognitive decline affects multiple cognitive domains in a similar way, leading to a decline in overall cognitive function. This means that interference effects would be present across all cognitive domains, regardless of their specific nature. Our results are consistent with a set of studies showing RI and associated inhibitory abilities are generally affected by aging and are responsible for increased interference effects in various domains (Andrés et al., 2008; Angel et al., 2013; Bugaiska & Thibaut, 2015; Burke & Osborne, 2007; Campbell et al., 2020; Collette et al., 2001; Collette & Salmon, 2014; Dey et al., 2017; Hasher et al., 1999, 2008; Hasher & Zacks, 1988; Lustig et al., 2007; Rowe et al., 2010; Stoltzfus et al., 1996). However, this does not necessarily imply that RI abilities themselves are domain-general. Indeed, aging is associated with cognitive decline in multiple cognitive domains, including attention, working memory and cognitive control more broadly, which will influence performance in various sets of tasks, including those used in this study, even if underlying task processes are distinct (Grady et al., 2006; Murman, 2015). This is also in line with neuroimaging studies showing overall reduction in gray matter volume and decreased neural connectivity (Murphy et al., 2021; Raz, 2000; Sala-Llonch et al., 2015; Yuan & Raz, 2014). In a related manner, Attout et al. (2022) showed that even if the same inferior frontal areas show increased activity during the resolution of phonological and semantic RI, the processes and representations involved are not the same. Multivariate neural patterns indeed differed for phonological and semantic RI. Hence, a common age effect for phonological, semantic, and visual RI does not necessarily imply that the processes involved are domain-general.

Another part of our results supports indeed a more domain/task specific view of RI processes. First, the age effect interacted with the domain effect for accuracy in the recent negative task and for the response-time based interference score when including the two tasks in the same analysis, with stronger age-related RI effects for the phonological or the semantic domains as compared to the visual domain. The correlation analyses also further show that the common age effects observed in the ANOVA design cannot necessarily be taken as evidence for domain-general RI abilities. Our correlation analysis overwhelmingly supported an absence of correlation, in either the young or the elderly groups, for RI effects between domains. Importantly, even within-domain correlations were supported with evidence for their absence. The only (few) correlations supported by evidence for their presence were mainly task-specific correlations. Our results mirror to some extent those of a study by McCall et al. (2022) which also carried out ANOVAs and correlation analyses, but by comparing aphasic and healthy control participants rather than young and elderly participants. The authors of that study observed a general group effect for phonological and semantic RI scores but no significant group-specific correlations between the different RI scores, leading them to conclude that RI abilities are domain-specific. The results of the present study suggest that RI abilities are even more specific. As already noted, the few robust correlations we observed were within-task rather than between-task correlations. Our results argue for task-specific RI abilities, in line with recent computational approaches of cognitive control, including RI. Verbeke and Verguts (2021) proposed a computational model based on the synchronization of neural oscillations between prefrontal control systems and posterior domain-specific representational domains. These synchronization processes are adapted as a function of the nature and domain of the task, by temporarily connecting prefrontal control systems and the specific representational substrates that are needed for carrying out a specific task. These adaptations can furthermore be made more efficient via procedural learning processes (Verguts & Notebaert, 2009). This approach implies that there will be as many different neural and cognitive configurations for RI as there are different task and domains and highlights the importance of specific procedures and rules for each task, which can be acquired through experience and training (Huycke et al., 2022). At the same time, a general age effect on RI should still be expected as the establishment and reconfiguration of the different neural systems involved in different RI tasks will be become less efficient due to general loss of neural connectivity in aging (Varangis et al., 2019).

One final question we need to address concerns the sensitivity of the different task and domain conditions for eliciting interference. Regarding accuracy and response time interference scores, the Task effect explained 23% and 24% of the variance. Overall, participants seemed more impacted by interference in the similarity-judgement task compared to the recent-negative task. There was also a Domain effect, but only for response time interference scores (22% of variance explained), with the semantic domain leading to a globally lesser interference effect than the two other domains. The Task effect and the Domain cannot be accounted for by sensory differences. Both auditory formats were used for presentation of critical verbal information in the phonological and semantic versions of both tasks. Regarding the Task effect, the level of conflict induced by the similarity judgment task may have been stronger than in the recent negative task, given that two test items had to be compared to two target items; in the recent negatives task, a single test word was presented, and its level of interference depended on target items that were not present anymore. Hence, determining whether RI processes are domain-specific or not based on RI effect size differences between tasks would not be an appropriate strategy. The same rationale can be applied to Domain effects, even if these were highly limited in this study and only reliably observed for response times. By definition, semantic information is characterized by highly associated information that can easily get co-activated, meaning that processing of seemingly unrelated semantic information may already involve some potential for interference, overall reducing differences in processing times for unrelated vs. related semantic information. It should however be noted here that this possible interpretation is not likely to explain the few interactions we observed between Age and Domains for RI effects, as they concerned higher and not reduced RI effects, and this for both phonological and semantic domains, relative to the visual domain.

Conclusions

Taken together, the results of this study support a view in which RI processes are highly specific. This specificity is however not inconsistent with a general age effect on RI abilities across tasks and domains as also observed in this study. We propose that age-related decreases in neural connectivity may prevent the specific neural reconfigurations necessary for dealing with interference in specific task and domain contexts, a hypothesis that calls for future empirical testing.

Supplementary Data

Reading Keys for Bayesian Model Comparisons (Bergh et al., 2020):

- P|M represents the prior model probabilities,
- P(M|data) represents the posterior model probabilities
- BF_M shows the change in model odds from prior to posterior
- The BF_{10} column lists the Bayes factors for each model against the null model
- The error % column indicates the percentage of error associated with each model comparison

Table 2

Descriptive data for Accuracy in terms of Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference), and Groups (Young, Elderly) for the Similarity-Judgement Task.

							95% Credible Interval	
Domains	Conditions	Groups	Mean	SD	SE	N	Lower	Upper
Visual	Facilitation	Young	0.99	0.03	2.92e-3	111	0.98	0.99
		Elderly	0.95	0.07	6.91e-3	99	0.93	0.96
	Interference	Young	0.91	0.10	9.69e-3	111	0.89	0.93
		Elderly	0.69	0.25	0.03	99	0.64	0.74
Phonological	Facilitation	Young	0.94	0.05	4.29e-3	111	0.93	0.95
		Elderly	0.86	0.12	0.01	99	0.83	0.88
	Interference	Young	0.87	0.20	0.02	111	0.83	0.91
		Elderly	0.66	0.25	0.02	99	0.61	0.71
Semantic	Facilitation	Young	0.97	0.04	4.26e-3	111	0.97	0.98
		Elderly	0.95	0.10	0.01	99	0.93	0.97
	Interference	Young	0.87	0.08	7.83e-3	111	0.86	0.89
		Elderly	0.62	0.27	0.03	99	0.57	0.68

Table 2

Model comparison for Bayesian Repeated Measures ANOVA conducted on Accuracy with Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference), and Groups (Young, Elderly) for the Similarity-Judgement Task.

Models	**P(M)**	**P(M|data)**	**BF_M**	**BF_{10}**	**error %**
Null model (incl. subject and random slopes)	0.05	4.61e-77	8.30e-76	1.00	
Domains + Conditions + Groups + Domains ✻ Conditions + Conditions ✻ Groups	0.05	0.87	119.08	1.88e+76	4.75
Domains + Conditions + Groups + Domains ✻ Conditions + Domains ✻ Groups + Conditions ✻ Groups + Domains ✻ Conditions ✻ Groups	0.05	0.10	1.95	2.12e+75	7.60
Domains + Conditions + Groups + Domains ✻ Conditions + Domains ✻ Groups + Conditions ✻ Groups	0.05	0.03	0.61	7.11e+74	4.85
Domains + Conditions + Groups + Conditions ✻ Groups	0.05	7.15e-4	0.01	1.55e+73	3.01
Domains + Conditions + Groups + Domains ✻ Groups + Conditions ✻ Groups	0.05	2.51e-5	4.51e-4	5.44e+71	3.07
Conditions + Groups + Conditions ✻ Groups	0.05	3.21e-7	5.78e-6	6.97e+69	4.50
Domains + Conditions + Groups + Domains ✻ Conditions	0.05	1.57e-16	2.83e-15	3.42e+60	2.50
Domains + Conditions + Groups + Domains ✻ Conditions + Domains ✻ Groups	0.05	6.31e-18	1.14e-16	1.37e+59	4.46
Domains + Conditions + Groups	0.05	1.65e-19	2.97e-18	3.58e+57	4.50
Domains + Conditions + Groups + Domains ✻ Groups	0.05	6.10e-21	1.10e-19	1.32e+56	5.08
Conditions + Groups	0.05	6.87e-23	1.24e-21	1.49e+54	2.40
Domains + Conditions + Domains ✻ Conditions	0.05	4.99e-37	8.98e-36	1.08e+40	2.87
Domains + Conditions	0.05	5.15e-40	9.27e-39	1.12e+37	2.31
Conditions	0.05	2.22e-43	4.00e-42	4.82e+33	1.92
Domains + Groups	0.05	3.20e-53	5.75e-52	6.93e+23	2.37
Domains + Groups + Domains ✻ Groups	0.05	1.16e-54	2.09e-53	2.52e+22	2.52
Groups	0.05	1.42e-56	2.55e-55	3.07e+20	2.46
Domains	0.05	9.90e-74	1.78e-72	2148.30	1.71

Note. All models include subject and random slopes for all repeated measures factors.

Table 3

Descriptive data for Response Times in terms of Domains (Phonological, Semantic, Visual), Condition (Facilitation, Interference), and Groups (Young, Elderly) for the Similarity-Judgement Task.

							95% Credible Interval	
Domains	Conditions	Groups	Mean	SD	SE	N	Lower	Upper
Visual	Facilitation	Young	750.61	308.88	29.45	110	692.24	808.98
		Elderly	1373.63	488.92	49.39	98	1275.61	1471.66
	Interference	Young	989.93	493.16	47.02	110	896.73	1083.12
		Elderly	1764.41	591.48	59.75	98	1645.82	1882.99
Phonological	Facilitation	Young	1339.97	362.22	34.54	110	1271.52	1408.42
		Elderly	1903.28	391.23	39.52	98	1824.85	1981.72
	Interference	Young	1620.65	402.74	38.40	110	1544.54	1696.75
		Elderly	2245.53	428.90	43.33	98	2159.55	2331.52
Semantic	Facilitation	Young	1186.20	251.18	23.95	110	1138.74	1233.67
		Elderly	1655.86	436.78	44.12	98	1568.29	1743.43
	Interference	Young	1257.73	321.38	30.64	110	1197.00	1318.46
		Elderly	1944.14	494.62	49.96	98	1844.97	2043.30

Note. One subject per group was removed from the data as their speed processing measure was missing.

Table 4

Model comparison for Bayesian Repeated Measures ANOVA conducted on Response Times with Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference) and Groups (Young, Elderly) for the Similarity-Judgement Task.

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject and random slopes)	0.03	4.92e-149	1.82e-147	1.00	
Domains + Conditions + XO + Groups + Domains ✻ Conditions + Domains ✻ Groups + Conditions ✻ Groups + Domains ✻ Conditions ✻ Groups	0.03	0.59	52.34	1.19e+148	5.73
Domains + Conditions + XO + Groups + Domains ✻ Conditions + Conditions ✻ Groups	0.03	0.28	14.66	5.77e+147	8.39
Domains + Conditions + XO + Groups + Domains ✻ Conditions + Domains ✻ Groups + Conditions ✻ Groups	0.03	0.13	5.55	2.65e+147	9.84
Domains + Conditions + XO + Groups + Domains ✻ Conditions	0.03	1.47e-6	5.44e-5	2.99e+142	6.63
Domains + Conditions + XO + Groups + Domains ✻ Conditions + Domains ✻ Groups	0.03	8.58e-7	3.18e-5	1.75e+142	3.59
Domains + Conditions + XO + Groups + Conditions ✻ Groups	0.03	1.88e-7	6.94e-6	3.81e+141	15.76
Domains + Conditions + XO + Groups + Domains ✻ Groups + Conditions ✻ Groups	0.03	1.18e-7	4.38e-6	2.41e+141	24.39
Domains + Conditions + Groups + Domains ✻ Conditions + Domains ✻ Groups + Conditions ✻ Groups + Domains ✻ Conditions ✻ Groups	0.03	1.45e-8	5.38e-7	2.96e+140	5.70
Domains + Conditions + Groups + Domains ✻ Conditions + Conditions ✻ Groups	0.03	7.10e-9	2.63e-7	1.44e+140	5.71
Domains + Conditions + Groups + Domains ✻ Conditions + Domains ✻ Groups + Conditions ✻ Groups	0.03	4.35e-9	1.61e-7	8.84e+139	4.30
Domains + Conditions + XO + Groups	0.03	9.14e-13	3.38e-11	1.86e+136	9.80
Domains + Conditions + XO + Groups + Domains ✻ Groups	0.03	5.03e-13	1.86e-11	1.02e+136	3.86
Domains + Conditions + Groups + Domains ✻ Conditions	0.03	2.86e-14	1.06e-12	5.81e+134	7.03
Domains + Conditions + Groups + Domains ✻ Conditions + Domains ✻ Groups	0.03	1.63e-14	6.02e-13	3.31e+134	5.42
Domains + Conditions + Groups + Conditions ✻ Groups	0.03	2.86e-15	1.06e-13	5.82e+133	3.59
Domains + Conditions + Groups + Domains ✻ Groups + Conditions ✻ Groups	0.03	1.69e-15	6.26e-14	3.44e+133	4.09
Domains + Conditions + XO + Domains ✻ Conditions	0.03	8.29e-17	3.07e-15	1.68e+132	8.24
Domains + Conditions + Groups	0.03	1.41e-20	5.20e-19	2.86e+128	3.31
Domains + Conditions + Groups + Domains ✻ Groups	0.03	7.78e-21	2.88e-19	1.58e+128	2.30
Domains + Conditions + XO	0.03	7.52e-23	2.78e-21	1.53e+126	3.56
Domains + Conditions + Domains ✻ Conditions	0.03	7.18e-44	2.66e-42	1.46e+105	3.18

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Domains + Conditions	0.03	3.75e-50	1.39e-48	7.62e+98	1.72
Domains + XO + Groups	0.03	2.10e-59	7.78e-58	4.27e+89	3.56
Domains + XO + Groups + Domains ✻ Groups	0.03	1.13e-59	4.16e-58	2.29e+89	3.31
Conditions + XO + Groups + Conditions ✻ Groups	0.03	8.99e-60	3.33e-58	1.83e+89	4.73
Conditions + XO + Groups	0.03	4.77e-65	1.76e-63	9.69e+83	3.03
Domains + Groups	0.03	3.30e-67	1.22e-65	6.72e+81	2.75
Conditions + Groups + Conditions ✻ Groups	0.03	2.03e-67	7.52e-66	4.13e+81	15.71
Domains + Groups + Domains ✻ Groups	0.03	1.88e-67	6.96e-66	3.82e+81	2.63
Domains + XO	0.03	1.73e-69	6.40e-68	3.52e+79	2.53
Conditions + Groups	0.03	1.04e-72	3.84e-71	2.11e+76	20.72
Conditions + XO	0.03	3.97e-75	1.47e-73	8.07e+73	4.35
Domains	0.03	9.39e-97	3.47e-95	1.91e+52	5.65
Conditions	0.03	2.23e-102	8.25e-101	4.53e+46	1.98
XO + Groups	0.03	1.19e-111	4.40e-110	2.42e+37	2.87
Groups	0.03	1.95e-119	7.23e-118	3.97e+29	2.76
XO	0.03	9.87e-122	3.65e-120	2.01e+27	3.04

Note. All models include subject, and random slopes for all repeated measures factors.

Table 5

Descriptive data for Accuracy in terms of Domains (Phonological, Semantic, Visual), Conditions (Neutral, Interfering N0, Interfering N+1) and Groups (Young adults, Elderly adults) for the Recent-Negative task.

							95% Credible Interval	
Domains	Conditions	Groups	Mean	SD	SE	N	Lower	Upper
Visual	Neutral	Young	0.96	0.05	4.60e-3	111	0.95	0.97
		Elderly	0.92	0.12	0.01	99	0.90	0.94
	Interfering N0	Young	0.67	0.13	0.01	111	0.64	0.69
		Elderly	0.60	0.16	0.02	99	0.57	0.63
	Interfering N+1	Young	0.90	0.09	8.69e-3	111	0.88	0.92
		Elderly	0.83	0.13	0.01	99	0.80	0.86
Phonological	Neutral	Young	0.94	0.06	5.89e-3	111	0.93	0.96
		Elderly	0.82	0.16	0.02	99	0.79	0.85
	Interfering N0	Young	0.48	0.17	0.02	111	0.44	0.51
		Elderly	0.35	0.22	0.02	99	0.31	0.40
	Interfering N+1	Young	0.81	0.10	9.82e-3	111	0.80	0.83
		Elderly	0.67	0.17	0.02	99	0.63	0.70
Semantic	Neutral	Young	0.93	0.07	6.94e-3	111	0.92	0.94
		Elderly	0.87	0.10	0.01	99	0.85	0.89
	Interfering N0	Young	0.93	0.07	7.05e-3	111	0.92	0.94
		Elderly	0.86	0.12	0.01	99	0.84	0.88
	Interfering N+1	Young	0.90	0.08	7.86e-3	111	0.88	0.92
		Elderly	0.83	0.13	0.01	99	0.81	0.86

Table 6

Model comparison for Bayesian Repeated Measures ANOVA conducted on Accuracy with Domains (Phonological, Semantic, Visual), Conditions (Neutral, N0 Interfering, N+1 Interfering) and Groups (Young, Elderly) for the Recent-Negative Task.

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject and random slopes)	0.05	0.00	0.00	1.00	
Domains + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions	0.05	0.95	359.35	∞	3.29
Domains + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions + Groups ✻ Conditions	0.05	0.05	0.89	∞	2.87
Domains + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions + Groups ✻ Conditions + Domains ✻ Groups ✻ Conditions	0.05	3.95e-4	7.11e-3	∞	9.22
Domains + Groups + Conditions + Domains ✻ Conditions	0.05	2.56e-4	4.61e-3	∞	1.93
Domains + Groups + Conditions + Domains ✻ Conditions + Groups ✻ Conditions	0.05	1.26e-5	2.27e-4	∞	2.20
Domains + Conditions + Domains ✻ Conditions	0.05	1.37e-16	2.46e-15	∞	20.08
Domains + Groups + Conditions + Domains ✻ Groups	0.05	5.61e-206	1.01e-204	2.23e+230	1.96
Domains + Groups + Conditions + Domains ✻ Groups + Groups ✻ Conditions	0.05	1.57e-207	2.83e-206	6.24e+228	3.57
Domains + Groups + Conditions	0.05	1.11e-208	2.00e-207	4.41e+227	11.17
Domains + Groups + Conditions + Groups ✻ Conditions	0.05	3.15e-210	5.67e-209	1.25e+226	17.94
Domains + Conditions	0.05	7.43e-221	1.34e-219	2.95e+215	1.56
Groups + Conditions	0.05	3.85e-290	6.92e-289	1.53e+146	1.61
Groups + Conditions + Groups ✻ Conditions	0.05	9.85e-292	1.77e-	3.91e+144	2.10

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Conditions	0.05	3.05e-302	290 5.48e-301	1.21e+134	1.05
Domains + Groups + Domains ✻ Groups	0.05	0.00	0.00	1.51e+92	2.98
Domains + Groups	0.05	0.00	0.00	8.84e+89	1.47
Domains	0.05	0.00	0.00	1.49e+78	35.17
Groups	0.05	0.00	0.00	6.77e+11	1.84

Note. All models include subject, and random slopes for all repeated measures factors.

Table 7

Descriptive data for Response Times in terms of Domains (Phonological, Semantic, Visual), Conditions (Neutral, N0 Interfering, N+1 Interfering) and Groups (Young, Elderly) for the Recent-Negative Task.

							95% Credible Interval	
		Group	N	Mean	SD	SE	Lower	Upper
Visual	Neutral	Young	110	1059.66	278.04	26.51	1007.11	1112.20
		Elderly	97	1457.77	324.26	32.92	1392.42	1523.13
	Interfering N0	Young	110	1380.64	335.93	32.03	1317.16	1444.12
		Elderly	97	1792.90	374.78	38.05	1717.37	1868.44
	Interfering N+1	Young	110	1227.73	303.19	28.91	1170.44	1285.03
		Elderly	97	1619.52	355.90	36.14	1547.79	1691.25
Phonological	Neutral	Young	110	522.34	249.19	23.76	475.25	569.43
		Elderly	97	932.37	400.13	40.63	851.72	1013.01
	Interfering N0	Young	110	785.28	366.80	34.97	715.96	854.59
		Elderly	97	1152.84	388.34	39.43	1074.58	1231.11
	Interfering N+1	Young	110	593.95	261.69	24.95	544.50	643.40
		Elderly	97	1014.12	395.60	40.17	934.38	1093.85
Semantic	Neutral	Young	110	696.18	289.87	27.64	641.40	750.95
		Elderly	97	1093.40	410.99	41.73	1010.57	1176.23
	Interfering N0	Young	110	741.72	314.65	30.00	682.26	801.18
		Elderly	97	1141.45	429.08	43.57	1054.97	1227.93
	Interfering N+1	Young	110	721.84	302.16	28.81	664.74	778.94
		Elderly	97	1120.27	398.52	40.46	1039.95	1200.59

Note. One subject per group were removed from the data as their speed processing measure was missing. Also, another elderly subject was discarded from this analysis as he/she got no corresponding RT score in one sub condition.

Table 8

Model comparison for Bayesian Repeated Measures ANOVA conducted on Response Times with Domains (Phonological, Semantic, Visual), Conditions (Neutral, N0 Interfering, N+1 Interfering) and Groups (Young, Elderly) for the Recent-Negative Task.

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject and random slopes)	0.03	3.75e-267	1.39e-265	1.00	
Domains + XO + Groups + Conditions + Domains ✻ Conditions	0.03	0.94	546.16	2.50e+266	9.36
Domains + XO + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions	0.03	0.04	1.42	9.83e+264	10.59
Domains + XO + Groups + Conditions + Domains ✻ Conditions + Groups ✻ Conditions	0.03	0.02	0.87	6.15e+264	26.71
Domains + XO + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions + Groups ✻ Conditions	0.03	1.89e-3	0.07	5.04e+263	41.51
Domains + XO + Conditions + Domains ✻ Conditions	0.03	1.61e-3	0.06	4.30e+263	4.77
Domains + XO + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions + Groups ✻ Conditions + Domains ✻ Groups ✻ Conditions	0.03	3.21e-5	1.19e-3	8.56e+261	59.08
Domains + Groups + Conditions + Domains ✻ Conditions	0.03	2.66e-6	9.86e-5	7.11e+260	2.84
Domains + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions	0.03	1.48e-7	5.48e-6	3.95e+259	13.99
Domains + Groups + Conditions + Domains ✻ Conditions + Groups ✻ Conditions	0.03	5.30e-8	1.96e-6	1.41e+259	2.76
Domains + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions + Groups ✻ Conditions	0.03	2.80e-9	1.04e-7	7.48e+257	4.42
Domains + Groups + Conditions + Domains ✻ Groups + Domains ✻ Conditions + Groups ✻ Conditions + Domains ✻ Groups ✻ Conditions	0.03	5.82e-11	2.15e-9	1.55e+256	3.66
Domains + Conditions + Domains ✻ Conditions	0.03	8.16e-22	3.02e-20	2.18e+245	2.97
Domains + XO + Groups + Conditions	0.03	3.56e-43	1.32e-41	9.50e+223	8.81
Domains + XO + Groups + Conditions + Domains ✻ Groups	0.03	1.18e-44	4.36e-43	3.15e+222	7.72
Domains + XO + Groups + Conditions + Groups ✻ Conditions	0.03	4.91e-45	1.82e-43	1.31e+222	8.66
Domains + XO + Conditions	0.03	5.11e-46	1.89e-44	1.36e+221	3.28
Domains + XO + Groups + Conditions + Domains ✻ Groups + Groups ✻ Conditions	0.03	1.35e-46	4.98e-45	3.59e+220	9.99
Domains + Groups + Conditions	0.03	7.54e-49	2.79e-47	2.01e+218	5.33
Domains + Groups + Conditions + Domains ✻ Groups	0.03	2.98e-50	1.10e-48	7.94e+216	1.64
Domains + Groups + Conditions + Groups ✻ Conditions	0.03	1.24e-50	4.59e-49	3.31e+216	2.19
Domains + Groups + Conditions + Domains ✻ Groups + Groups ✻ Conditions	0.03	5.85e-52	2.16e-50	1.56e+215	5.93

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Domains + Conditions	0.03	1.95e-64	7.22e-63	5.20e+202	1.31
Domains + XO + Groups	0.03	9.12e-114	3.37e-112	2.43e+153	1.94
Domains + XO + Groups + Domains ✻ Groups	0.03	3.64e-115	1.35e-113	9.70e+151	7.66
Domains + XO	0.03	1.40e-116	5.19e-115	3.74e+150	2.72
Domains + Groups	0.03	1.93e-119	7.13e-118	5.14e+147	2.97
Domains + Groups + Domains ✻ Groups	0.03	7.71e-121	2.85e-119	2.06e+146	2.13
Domains	0.03	5.09e-135	1.88e-133	1.36e+132	1.44
XO + Groups + Conditions	0.03	2.71e-175	1.00e-173	7.23e+91	2.46
XO + Groups + Conditions + Groups ✻ Conditions	0.03	4.58e-177	1.70e-175	1.22e+90	1.82
XO + Conditions	0.03	4.06e-178	1.50e-176	1.08e+89	1.88
Groups + Conditions	0.03	5.49e-181	2.03e-179	1.46e+86	1.89
Groups + Conditions + Groups ✻ Conditions	0.03	9.96e-183	3.69e-181	2.66e+84	3.29
Conditions	0.03	1.52e-196	5.63e-195	4.06e+70	1.14
XO + Groups	0.03	6.98e-246	2.58e-244	1.86e+21	1.44
XO	0.03	1.05e-248	3.90e-247	2.81e+18	1.57
Groups	0.03	1.39e-251	5e-250	3.71e+15	2.63

Note. All models include subject, and random slopes for all repeated measures factors.

Table 9. Descriptive data for the Accuracy Interference Score in terms of Domains (Phonological, Semantic, Visual), Tasks (Similarity-Judgement, Recent-Negative) and Groups (Young adults, Elderly adults).

							95% Credible Interval	
Domains	Tasks	Groups	Mean	SD	SE	N	Lower	Upper
Visual	Recent-Negative	Young	0.06	0.09	8.33e-3	111	0.05	0.08
		Elderly	0.07	0.29	0.03	99	0.01	0.13
	Similarity-Judgement	Young	0.08	0.11	0.01	111	0.06	0.10
		Elderly	0.27	0.26	0.03	99	0.22	0.32
Phonological	Recent-Negative	Young	0.14	0.10	9.88e-3	111	0.12	0.16
		Elderly	0.17	0.22	0.02	99	0.13	0.22
	Similarity-Judgement	Young	0.08	0.21	0.02	111	0.04	0.12
		Elderly	0.23	0.27	0.03	99	0.18	0.28
Semantic	Recent-Negative	Young	0.03	0.09	8.13e-3	111	0.01	0.04
		Elderly	0.04	0.12	0.01	99	0.02	0.07
	Similarity-Judgement	Young	0.11	0.08	8.01e-3	111	0.09	0.12
		Elderly	0.35	0.26	0.03	99	0.30	0.40

Table 10

Model comparison for Bayesian Repeated Measures ANOVA conducted on accucary Interference Score with Domains (Phonological, Semantic, Visual), Tasks (Similarity-Judgement, Recent-Negative) and Groups (Young, Elderly).

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject and random slopes)	0.05	1.96e-41	3.52e-40	1.00	
Domains + Groups + Tasks + Domains ✻ Tasks + Groups ✻ Tasks	0.05	0.89	141.13	4.53e+40	3.43
Domains + Groups + Tasks + Domains ✻ Groups + Domains ✻ Tasks + Groups ✻ Tasks	0.05	0.06	1.23	3.26e+39	3.12
Domains + Groups + Tasks + Domains ✻ Groups + Domains ✻ Tasks + Groups ✻ Tasks + Domains ✻ Groups ✻ Tasks	0.05	0.05	0.94	2.52e+39	3.87
Domains + Groups + Tasks + Domains ✻ Tasks	0.05	3.49e-9	6.28e-8	1.78e+32	2.79
Domains + Groups + Tasks + Domains ✻ Groups + Domains ✻ Tasks	0.05	2.93e-10	5.27e-9	1.50e+31	12.00
Groups + Tasks + Groups ✻ Tasks	0.05	1.50e-13	2.70e-12	7.66e+27	4.30
Domains + Groups + Tasks + Groups ✻ Tasks	0.05	7.45e-14	1.34e-12	3.81e+27	17.05
Domains + Groups + Tasks + Domains ✻ Groups + Groups ✻ Tasks	0.05	4.55e-15	8.19e-14	2.32e+26	7.88
Domains + Tasks + Domains ✻ Tasks	0.05	5.34e-21	9.62e-20	2.73e+20	5.80
Groups + Tasks	0.05	6.19e-22	1.11e-20	3.16e+19	1.64
Domains + Groups + Tasks	0.05	2.50e-22	4.50e-21	1.28e+19	2.52
Domains + Groups + Tasks + Domains ✻ Groups	0.05	2.11e-23	3.80e-22	1.08e+18	14.74
Groups	0.05	9.86e-30	1.78e-28	5.04e+11	1.55
Domains + Groups	0.05	4.18e-30	7.52e-29	2.13e+11	2.39
Domains + Groups + Domains ✻ Groups	0.05	2.80e-31	5.05e-30	1.43e+10	3.10
Tasks	0.05	1.19e-33	2.15e-32	6.10e+7	1.00
Domains + Tasks	0.05	5.00e-34	9.01e-33	2.56e+7	2.73
Domains	0.05	7.68e-42	1.38e-40	0.39	1.01

Note. All models include subject, and random slopes for all repeated measures factors.

Table 11

Descriptive data for the Response Times Interference Score in terms of Domains (Phonological, Semantic, Visual), Tasks (Similarity-Judgement, Recent-Negative) and Groups (Young adults, Elderly adults).

							95% Credible Interval	
Domains	Tasks	Groups	Mean	SD	SE	N	Lower	Upper
Visual	Recent-Negative	1	-0.17	0.16	0.01	111	-0.20	-0.14
		2	-0.12	0.11	0.01	99	-0.14	-0.09
	Similarity-Judgement	1	-0.30	0.27	0.03	111	-0.35	-0.25
		2	-0.31	0.27	0.03	99	-0.37	-0.26
Phonological	Recent-Negative	1	-0.18	0.33	0.03	111	-0.25	-0.12
		2	-0.12	0.24	0.02	99	-0.17	-0.07
	Similarity-Judgement	1	-0.22	0.17	0.02	111	-0.25	-0.19
		2	-0.20	0.17	0.02	99	-0.23	-0.16
Semantic	Recent-Negative	1	-0.05	0.18	0.02	111	-0.09	-0.02
		2	-0.04	0.16	0.02	99	-0.07	-6.37e-3
	Similarity-Judgement	1	-0.06	0.14	0.01	111	-0.08	-0.03
		2	-0.19	0.21	0.02	99	-0.23	-0.15

Table 12

Model comparison for Bayesian Repeated Measures ANOVA conducted on Response Times Interference Score with Domains (Phonological, Semantic, Visual), Tasks (Similarity-Judgement, Recent-Negative) and Groups (Young, Elderly).

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject and random slopes)	0.05	2.48e-31	4.46e-30	1.00	
Domains + Tasks + Groups + Domains ✻ Tasks + Domains ✻ Groups + Tasks ✻ Groups	0.05	0.67	36.97	2.72e+30	3.44
Domains + Tasks + Groups + Domains ✻ Tasks + Domains ✻ Groups + Tasks ✻ Groups + Domains ✻ Tasks ✻ Groups	0.05	0.21	4.81	8.52e+29	5.95
Domains + Tasks + Groups + Domains ✻ Tasks + Domains ✻ Groups	0.05	0.04	0.75	1.61e+29	5.16
Domains + Tasks + Groups + Domains ✻ Tasks + Tasks ✻ Groups	0.05	0.04	0.66	1.43e+29	3.54
Domains + Tasks + Domains ✻ Tasks	0.05	0.03	0.50	1.09e+29	5.54
Domains + Tasks + Groups + Domains ✻ Groups + Tasks ✻ Groups	0.05	0.01	0.20	4.39e+28	32.53
Domains + Tasks + Groups + Domains ✻ Tasks	0.05	2.00e-3	0.04	8.09e+27	1.88
Domains + Tasks + Groups + Domains ✻ Groups	0.05	4.22e-4	7.60e-3	1.70e+27	2.92
Domains + Tasks + Groups + Tasks ✻ Groups	0.05	3.80e-4	6.84e-3	1.53e+27	2.16
Domains + Tasks	0.05	2.97e-4	5.35e-3	1.20e+27	1.52
Domains + Tasks + Groups	0.05	2.76e-5	4.97e-4	1.11e+26	7.33
Domains + Groups + Domains ✻ Groups	0.05	1.65e-13	2.96e-12	6.65e+17	7.91
Domains	0.05	1.15e-13	2.07e-12	4.65e+17	1.17
Domains + Groups	0.05	9.24e-15	1.66e-13	3.73e+16	1.76
Tasks + Groups + Tasks ✻ Groups	0.05	4.27e-22	7.68e-21	1.72e+9	2.27
Tasks	0.05	3.95e-22	7.12e-21	1.60e+9	1.16
Tasks + Groups	0.05	3.10e-23	5.57e-22	1.25e+8	1.59
Groups	0.05	2.03e-32	3.65e-31	0.08	2.69

Note. All models include subject, and random slopes for all repeated measures factors.

The neural specificity of interference resolution in phonological, semantic, and visual domains at different ages

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In preparation

Abstract. The question of whether cognitive control is specific to certain domains or domain-general remains an extensively debated question at both cognitive and neural levels. This study examined the neural substrates associated with resistance-to-interference (RI) in phonological, semantic, and visual domains by using strictly matched tasks and determining the domain-general or domain-specific manner in which aging affects the neural substrates associated with RI. In an fMRI experiment, young and elderly participants performed a similarity-judgment task with phonological, semantic, or visual interference build-up. For both age groups, domain-specific RI effects were observed at the univariate level, with increased involvement in the phonological domain of the right angular gyrus and the right lingual gyrus, in the semantic domain of the bilateral inferior frontal gyrus (IFG), the bilateral superior parietal and angular gyri and the left middle temporal gyrus, and in the visual domain of the middle/superior frontal gyri and occipital gyri. At the multivariate level, although RI effects could be decoded from neural patterns in the bilateral IFG for all domains and age groups, between-domain prediction of RI conditions was associated with Bayesian evidence for the null hypothesis. This study supports the domain-specificity of neural substrates associated with RI while stressing its age-independency.

Keywords: resistance-to-interference ; inhibitory control; domain-specific; aging; MVPA; fMRI

Author notes

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Conflict of interest. There is no conflict of interest in connection with this work.

Ethical statement. This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by a local ethics committee (Comité d'Ethique Hospitalo-Facultaire Universitaire de Liège; file number: B707201939419).

Credit authorship contribution statement

CG: Conceptualization, Methodology, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Project administration.
LA: Conceptualization, Methodology, Resources.
CP: Formal analysis
LH: Data curation.
LR: Data Curation, Formal analysis.
SM: Conceptualization, Methodology, Formal analysis, Resources, Writing - original draft, Writing - review & editing, Supervision, Project administration.

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Open science statement. We report how we determined our sample size, and describe all data exclusions, and we follow the JARS (Appelbaum et al., 2018). Behavioural and neuroimaging data, analysis code, and research materials are available. This study's design and its analysis were not pre-registered. Each software used is presented and referenced in the manuscript. Supplementary data file and material can be found at https://osf.io/efmhc/.

Introduction

Resistance-to-interference (RI) refers to the ability to selectively attend to relevant information while inhibiting the processing of irrelevant information (Dempster & Corkill, 1999; Harnishfeger, 1995; Miyake, Friedman, Emerson, Witzki, Howerter, et al., 2000). This cognitive control process involves the ability to filter out or suppress irrelevant information to maintain the focus on task-relevant information. At the neural level, RI has been associated with the involvement of the inferior frontal gyrus (IFG) across different tasks and sensory modalities, but some task-related modulation of neural substrates has also been reported, raising the more general question of the domain-generality vs. domain-specificity of RI processes (Grégoire & Majerus, 2023; Kliegl & Bäuml, 2021; Nigg, 2000). This study provides a systematic investigation of the neural substrates supporting RI across phonological, semantic, and visual domains by furthermore examining their age-related invariance.

Several studies assessed the neural substrates associated with RI for visual stimuli (e.g., go-no task), generally highlighting the involvement of the bilateral or the right IFG (Chadick et al., 2014; McNab et al., 2008; Wager et al., 2005; Weeks et al., 2020; Zhu et al., 2010). These results were confirmed by several meta-analyses (Nee et al., 2007; Simmonds et al., 2008). Similarly, studies exploring RI for verbal tasks (e.g., color-word interference task; Stroop) also highlighted the involvement of the bilateral or left IFG (e.g., Gruber et al., 2002; Leung et al., 2000; Manard et al., 2017; Nelson et al., 2009; Parris et al., 2019; Peterson et al., 1999, 2002; Taylor et al., 1997; Thompson-Schill et al., 1997; van Veen et al., 2001). Few neuroimaging studies, however, have directly compared verbal and visual RI tasks. Some studies observed common involvement of the IFG (Funahashi, 2022; Kadota et al., 2010; S. Martin et al., 2006; Nathaniel-James, 2002), while others reported a potential left-right hemisphere distinction, with right IFG involvement for visual RI and left IFG involvement for verbal RI (Morimoto et al., 2008; Schumacher et al., 2011; Stephan et al., 2003). It should be noted, though, that the tasks used in these studies for comparing verbal vs. visual RI are often not comparable at a structural level, raising the possibility that the observed differences are due to task rather than to RI-process differences (see Grégoire & Majerus, 2023 for a discussion).

Furthermore, some studies have investigated potential differences for RI to phonological vs. semantic aspects of information within the verbal domain. One of the first studies of this kind is the study by Paulesu et al. (1997). The authors examined the neural substrates associated with phonemic and semantic fluency tasks. They found common involvement of the pars triangularis part of the IFG for both tasks, but they also observed higher activity in the pars opercularis of the left IFG for the phonological task and higher activity of the left retrosplenial cortex for the semantic task. Other studies contradict these findings. For example, Snyder et al. (2007) investigated RI for semantic and phonological information using similarity judgment tasks and found no differences in neural responses in the left IFG. Abel et al. (2009, 2012), by using picture-word interference paradigms, observed specific involvement of the left supramarginal gyrus for phonological RI and of the left orbitofrontal gyrus, left medial middle temporal gyrus, and left angular gyrus for semantic RI. Attout et al. (2022) recently compared semantic and phonological RI using a similarity judgment task. They observed that the pars triangularis of the bilateral IFG and the left middle temporal gyrus supported both phonological and semantic RI, with more widespread frontoparietal involvement for semantic RI. Importantly, the multivariate neural patterns associated with phonological RI in different IFG regions-of-interest could not predict neural patterns associated with semantic RI and vice versa (see also Gold et al., 2005; Klaus & Hartwigsen, 2019; Poldrack et al., 1999; Snyder et al., 2007). These results are also in line with neuropsychological findings. Using various paradigms such as the blocked cyclic naming paradigm (i.e., semantic interference is build-up by having participants repeatedly name the same pictures involving objects from the same or a different semantic/phonological category) or recent negative tasks (i.e., a list of words has to be remembered followed by a phonologically or semantically related test word that needs to be rejected), studies in brain-damaged patients with language control deficits have shown that semantic RI abilities can be specifically impaired (Biegler et al., 2008; Damian et al., 2001; Hamilton & Martin, 2005, 2007a; Jefferies et al., 2007b; T. T. Schnur et al., 2006, 2009b; Thompson et al., 2017). However, the possibility of a reverse dissociation, with preserved semantic but impaired phonological RI abilities, still needs to be demonstrated.

In sum, studies so far provide conflicting and fragmentary evidence regarding the common vs. shared neural substrates supporting RI across visual, phonological, and semantic domains. As noted earlier, direct comparisons with equivalent task designs have rarely been conducted. Furthermore, studies focusing on one RI domain did not necessarily control for the possible influence from another domain. For example, studies using faces or scenes to investigate visual RI may also involve verbal RI processes, given that verbal labels can be easily associated with this type of visual stimuli (e.g., Chadick et al., 2014; Weeks et al., 2020). Furthermore, tasks might have addressed different aspects of RI, with some tasks, particularly in studies probing visual RI, having a strong motor inhibition component (e.g., stop-signal tasks) that is less involved in verbal RI tasks such as the color-word interference Stroop task or verbal fluency tasks (Hampshire et al., 2010; Lenartowicz et al., 2011; Schaum et al., 2021). Critically, all studies (except one) reviewed here used univariate neuroimaging studies, potentially occulting domain-specific differences. The study by Attout et al. (2022), showing overlapping univariate but distinct multivariate neural substrates for phonological vs. semantic RI, stresses the importance of taking advantage of the increased sensitivity of multivariate methods. The present study systematically investigated the neural substrates of RI abilities across visual, phonological, and semantic domains, using structurally equivalent task designs and univariate and multivariate analysis methods.

Aging leads to larger individual differences in RI-related processes, as shown by a large number of studies (Andrés et al., 2008; Angel et al., 2013; Bugaiska & Thibaut, 2015; D. M. Burke & Osborne, 2007; Campbell et al., 2020; X. Chen et al., 2022; Collette et al., 2001; Collette & Salmon, 2014; Dey et al., 2017; Hasher et al., 1999; Hasher & Zacks, 1988; Lustig et al., 2007; McDonough & Madan, 2021; Rowe et al., 2010; Stoltzfus et al., 1996). At the same time, the meta-analysis of Rey-Mermet et al. (2018) revealed no conclusive evidence for a *general* age-related decline in RI, but other studies showed RI deficits for specific domains (Hedden & Park, 2001, 2003; Noiret et al., 2017; Peltsch et al., 2011; Schik et al., 2000). The investigation of the impact of age on RI across domains is, therefore, particularly informative for the purpose of this study, as age-related decline in RI may stem from shared or task/domain-specific neural substrates. Without directly or even indirectly comparing RI across domains, studies so far have observed that older adults tend to activate more extended neural networks associated with RI as task demands increase (Cabeza et al., 2018; Reuter-Lorenz & Cappell, 2008; Reuter-Lorenz & Park, 2010; see McDonough et al. (2022) for a recent review). However, when the amount of RI required exceeds individual RI capacity, neural activity in these networks may also lead to age-related decreases (Koen & Rugg, 2019; S.-C. Li et al., 2001; Reuter-Lorenz et al., 2001; Reuter-Lorenz & Park, 2014; Sebastian et al., 2013).

The present study systematically investigates the neural substrates of RI abilities across verbal and visual domains and their age-related changes. We contrasted RI for verbal versus visual domains as these are the most frequently studied domains for research on RI. Furthermore, within the verbal domain, we distinguished phonological vs. semantic aspects of the interfering verbal information given the earlier discussed emerging neuroimaging and neuropsychological evidence for a possible separation of phonological vs. semantic RI abilities. Critically, the same paradigm was used to examine RI across these three domains. The basic element of the paradigm was a similarity-judgment task previously used in the verbal domain for assessing RI to irrelevant semantic information (Thompson-Schill et al., 1997), with a recent adaptation to phonological RI (Attout et al., 2022). We further adapted the paradigm to include a visual RI condition. The task required participants to choose the test-item that provides the closest association with two target-items after the presentation of a prime stimulus that pre-activated specific semantic, phonological, or visual features. The preactivated features could either interfere with the selection of the correct test-item (RI condition) by priming the incorrect test-item or facilitate the selection of the correct test-item (facilitation condition) by priming the correct test-item. In order to maximize the contrast between the three different domains, we used nonwords for the phonological domain, words for the semantic domain, and multi-feature geometric shapes for the visual domain. The three subtasks were built to be as similar as possible at the structural level. At the behavioral level, we determined whether age effects for the RI score interacted with stimulus domain. At the neuroimaging level, we determined the overlap and differences of neural substrates associated with phonological, semantic, and visual RI conditions, at both univariate and multivariate levels, separately for each of the two age groups (young vs. elderly adults). Furthermore, we contrasted the neural substrates associated with RI in young vs. elderly participants to assess the domain-specificity of RI processes in the most sensitive manner. Critically, we examined, for each age group, whether the neural patterns characterizing RI in one domain (e.g., phonological) could predict those characterizing RI in another domain (e.g., visual).

Method

Participants

Sample size determination was informed by fMRIPower software http://www.fmripower.org, showing that a sample size of N = 30 (per age group) is required (power = .80; effect size = 0.75; α = 0.001) for assessing IFG univariate activity peaks in the RI vs. facilitation contrasts. We recruited 35 participants in each group to ensure the minimum number of 30 valid data sets was reached. None of the participants was taking any medication that could influence their cognitive functioning at the time of the test. Bayesian T-tests showed that the two groups were matched for level of education but, as in most aging studies, had higher receptive vocabulary knowledge (see Table 1). Those were confirmed with the Bayesian informative hypotheses evaluation Welch's T-Test. All the elderly participants included in the study had a Montreal Cognitive Assessment score larger than or equal to 23 (Carson et al., 2018; Nasreddine et al., 2005), confirming age-appropriate general cognitive status (M = 27.25, SD = 1.84, SE = 0.35, IC95 = [26.54; 27.96]). A financial compensation of 10 euros per hour of participation was provided to all participants. In line with the Declaration of Helsinki (1964), all participants gave written informed consent before their inclusion in the study, and the study was approved by the local ethics committee (Comité d'Ethique Hospitalo-Facultaire Universitaire de Liège; file number: B707201939419). The data from seven participants had to be excluded due to technical difficulties during fMRI acquisition. The final sample size comprised 34 young adults and 29 elderly adults. This study was not preregistered.

Table 3

Participant Characteristics (mean and standard deviation).

	Groups	N	Mean	SD	SE	Bayesian Factor	Bain Welch T-Test
Level of education	Young	34	15.44	1.96	0.34	BF_{10} = 0.39	BF_{10} = 0.21
	Elderly	29	14.97	1.80	0.33	BF_{01} = 2.55	BF_{01} = 4.35
Vocabulary level	Young	34	25.09	3.72	0.64	BF_{10} = 1.02+6	BF_{10} = 5.25+8
	Elderly	29	67.55	5.47	1.02		
Age	Young	34	24.47	2.87	0.49	BF_{10} = 2.07+39	BF_{10} = 8.23+27
	Elderly	29	29.31	2.88	0.53		

Similarity-Judgment Task

Material

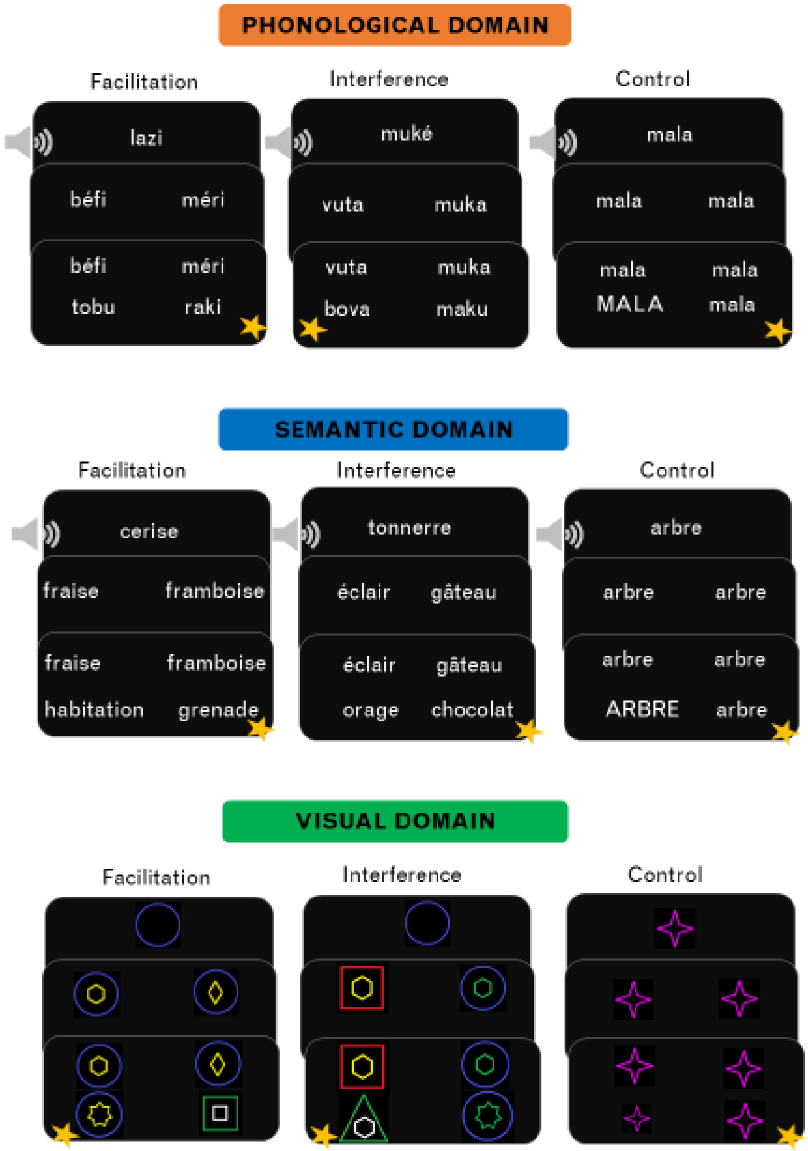
Phonological domain. The phonological similarity-judgment task required participants to match nonwords on a specific criterion. Participants were asked to choose the test nonword closest to both target nonwords, i.e., sharing a vowel in the same position. In the RI condition, the prime nonword, via its phonological similarity, pre-activated the wrong test nonwords. For example, for the target nonwords "vuta" and "muka", and the test nonwords “maku” and “bova”, the correct test nonword is “bova”, but the prime “muké” will pre-activate “muka” which then needs to be inhibited to allow for the correct test nonword to be chosen. In the facilitation condition, the prime nonword “lona” directly pre-activates the correct test nonword. A control condition that involved font-matching judgments was also included to control for perceptual and motor aspects (see Figure 1). The prime nonwords were recorded by a female voice for auditory presentation, in order to maximally ensure. The nonwords were selected from a pool of 63 consonant-vowel-consonant-vowel nonwords, based on Attout et al. (2022). For the facilitation conditions, the prime, both targets, and the correct answer shared the same vowel in the same position when the wrong item to select contained completely different consonants and vowels. In the interfering conditions, the prime shared a common letter and three consonants with one target nonword and one test nonword that should not be selected; the right answer shared the same vowel with both target nonwords at the same place.

Semantic domain. The semantic similarity-judgment task used the same structure as the phonological task, except that words were presented, and the test words had to be selected based on semantic similarity with both target words. In the RI condition, the prime word, via its semantic similarity, pre-activated the wrong test word. For example, for the target words "éclair - a French desert but also having the thunder-related meaning of electric strike” and “gâteau – cake” and the test words “orage - thunderstorm” and “chocolat - chocolate”, the correct test word is “chocolat”, but the prime “tonnerre - thunder” will pre-activate “orage” which then needs to be inhibited to allow for the correct test word to be chosen. In the facilitation condition, the prime nonword “glace - ice cream” would directly pre-activate the correct test nonword (see also Figure 1 for further examples). We selected 118 words controlled for concreteness, imageability, frequency, number of letters and syllables, number of phonological and orthographic neighbors, and orthographic and phonological uniqueness points values matched between the facilitation and interference lists (BF_{10} = [0.207 to 1.10], BF_{01} = [1.09 to 4.83], Bayesian Independent Samples T-test and descriptive data available in the Supplementary Material file. Psycholinguistics variables were extracted from the Lexique database (New et al., 2001, 2004), while concreteness, imageability, and emotional valence were taken from a database developed by Grégoire et al. (2023).

Visual domain. The visual similarity-judgment task followed the same structure as the two other tasks, except that coloured geometric shapes were presented, and the test stimuli had to be selected based on maximal visual similarity with both target stimuli (see Figure 1). Participants were asked to choose the test-symbol that had at least one common element with the two target-items, which were composed of internal and external geometric coloured shapes. For example, in the RI condition shown in Figure 1, the prime stimulus pre-activated the test stimulus with blue external circle, but this aspect was only shared with one of the two target stimuli; the correct answer was the test-stimulus with an internal hexagon as it was the element shared with both target items. In the facilitation condition depicted in Figure 1, the shape (○) and colour (blue) of the prime-stimulus were identical to both target items and to the correct answer, facilitating correct response selection. A control condition was also included to control for perceptual and motor aspects, where the same shape appeared for each stimulus type, with only the size differing between the target and test words. Participants had to select the test symbol presented in the same size as both target words. Visual stimuli were constructed from six geometric shapes (circle, heptagram, hexagon, diamond, square, triangle) and five colors (white, red, blue, yellow, green).

Figure 1

Illustration of the Phonological, Semantic, and Visual Similarity-Judgement Tasks, for Facilitation, Interfering, and Control Conditions.



Note. Yellow stars indicate the correct response.

Procedure

Before the experiment, the participants were given a practice session outside the magnetic resonance environment to familiarize themselves with the task requirements. This practice session included ten practice trials for each domain separately, then ten practice trials mixing the different domain conditions; the practice trials could be repeated until participants showed sufficient understanding of the task before entering the scanner. A T1-weighted structural brain scan was acquired after the task, as described below. The task was presented on a workstation that ran Matlab 15 and the Cogent toolbox (UCL, http://www.vislab.ucl.ac.uk/cogent.php). The auditory or visual prime stimuli were presented for 2000 ms, followed by the two target-stimuli on the upper part of the screen, and 2000 ms later, in addition to the two test-stimuli on the lower part of the screen. Participants had to select the correct test-item within 8000 ms by pushing a left key for selecting the test-stimulus on the left or the right key for selecting the test-stimulus on the right (on an MRI-compatible button box placed in their right-dominant hand). Each task had 26 facilitation trials, 26 RI trials, and 10 control trials. Right and left correct responses had the same probability. The three domain conditions were presented in the same session, with semi-randomized order between participants. The duration of the intertrial interval was variable (random Gaussian distribution centered on a mean duration of 7000 $\pm$ 1000 ms) and further varied as a function of the participants' response times since the probe array disappeared immediately after a response was recorded. If the participant did not respond within 8000 ms, 'no response' was recorded and the next trial began. Both response accuracy and response times were collected.

MRI acquisition

Whole-brain functional MRI time series were obtained using a 20-channel receiver head coil on a 3T scanner (Magnetom Prisma, Siemens Medical Solutions, Erlangen, Germany). The axial slice orientation was used to acquire multislice T2*-weighted functional images of the brain, covering 32 slices with a multiband factor of 2, a field of view of 192x192 mm^2, voxel size of 3x3x3 mm^3, 25% interslice gap, a matrix size of 64x64x32, a TR of 978 ms, TE of 30 ms, and a flip angle of 90°. The first five volumes were discarded to minimize T1 saturation effects. To correct for distortion, a gradient-recalled sequence was used to obtain two complex images with different echo times (TE = 10.00 and 12.46 ms), which generated field maps for distortion correction of the echo-planar images (EPI). Anatomical reference was obtained through high-resolution T1-weighted images (T1-weighted 3D magnetization-prepared rapid gradient echo (MPRAGE) sequence, TR = 1170 ms, TE = 2.19 ms, TI = 900 ms, FoV = 256x240 mm^2, matrix size = 256x240x224, voxel size = 1x1x1 mm^3). EPI time series were corrected for motion and distortion with "Realign and Unwarp" (Andersson et al. 2001) using the generated field map together with the FieldMap toolbox (Hutton et al. 2002) provided in SPM12. A mean realigned functional image was then calculated by averaging all the realigned and unwarped functional scans and the structural T1-image was coregistered to this mean functional image (using a rigid body transformation optimized to maximize the normalized mutual information between the two images). The visual stimuli were displayed on a screen placed at the back of the scanner, visible to the participant through a mirror attached to the head coil.

Data analysis

For behavioral analyses and multivariate analysis, a Bayesian statistical approach was utilized (Wagenmakers, 2007). Contrary to frequentist statistics, Bayesian analyses compute evidence against or in favor of a given model along a continuous dimension (the Bayes factor values - BF) rather than deciding on the presence of an effect based on an arbitrary statistical threshold (Schönbrodt & Wagenmakers, 2018). Bayesian statistics also reduce Type-1 error probability (Schönbrodt et al., 2017). The BF_{10} value represents the likelihood ratio of the alternative model (H_1) relative to the null model (H_0); the likelihood ratio of H_0 relative to H_1 corresponds to the reverse, $BF_{01} = 1/BF_{10}$. The following classification of strength of evidence was used (Jeffreys, 1961; Lee & Wagenmakers, 2014): A BF of 1 provides no evidence, 3 > BF > 1 provides anecdotal evidence, 10 > BF > 3 provides moderate evidence, 30 > BF > 10 provides strong evidence, 100 > BF > 30 provides very strong evidence, and BF > 100 provides extreme/decisive evidence. Bayesian analyses were conducted with Version 0.16.3 of the Bayesian JASP software package, using default settings for the Cauchy prior distribution (JASP Team, 2023, https://jasp-stats.org/) and random slopes for repeated-measures interaction (Bergh et al., 2022), r scale of the Cauchy distribution for t-tests was set to .707; the r scale was set to .5 and 1, for ANOVA fixed effect and random effects, respectively. Bayesian post-hoc tests were performed with Bayesian Paired and Independent Samples T-Tests. Note that for each Bayesian ANOVA performed, descriptive data and full model comparison tables are presented in the Supplementary Data file. In the manuscript, the same notation as the one from JASP was used to display Bayes Factors. For example, BF_{10} = 1.29e+12 means BF_{10} = $1.29*10^{12}$. Finally, for univariate analyses of neuroimaging data, frequentist statistics were used to ensure that our data could be interpreted relative to previous studies which used exclusively frequentist statistics.

Univariate analyses

Univariate analyses isolated BOLD signal variations associated with the RI effect in each task. Each participant's BOLD responses were estimated at each voxel, using a general linear model with epoch regressors and event-related regressors. For both tasks, the regressor ranged from the onset of the probe display to the participant’s response, where RI is required. On this basis, for each domain, two linear contrasts were performed, one for the interfering condition and another for the facilitation condition, resulting in six linear contrasts of interest. For each model, the design matrix also included the realignment parameters to account for any residual movement-related effect. A high-pass filter was implemented using a cut-off period of 128 sec in order to remove the low-frequency drifts from the time series. Serial autocorrelations were estimated with a restricted maximum likelihood algorithm with an autoregressive model of order one plus white noise. After smoothing (5-mm FWHM Gaussian kernel), the contrast images (for RI – facilitation) for this regressor were then entered in a second-level (random effects) analysis; see the open-repository for easy access. ANOVAs were performed to assess the significance of the RI effects. All the univariate analyses were performed using a cluster-level family-wise error rate corrected (FWEc) threshold at $P < 0.05$, with a voxel-level cluster forming threshold of $P < 0.001$. For regions of interest (ROI) analyses, a small volume correction was applied to the contrasts of interests (Eklund et al., 2016). Conjunction analysis testing the conjunction null hypothesis (Friston et al., 2005) was also conducted to determine the extent of overlap of brain regions associated with RI across domains and groups. Univariate analyses were performed on Matlab 2015b (https://www.mathworks.com/matlab.html) using SPM 12.3 (https://www.fil.ion.ucl.ac.uk/spm).

A priori Regions-of-Interest

ROIs were determined a priori using the WFU Pick Atlas on Matlab (Maldjian et al., 2003, 2004, https://www.nitrc.org/projects/wfu_pickatlas/) by exporting the three subparts of the inferior frontal gyrus: the pars opercularis (BA 44), the pars orbitalis (BA 47), and the pars triangularis (BA 45) from the IBASPM 116 tool. After performing the univariate ANOVA, each significant MNI coordinate was checked with the WFU Pick Atlas and the BioImage application (Lacadie et al., 2008; https://bioimagesuiteweb.github.io/webapp/mni2tal.html) to obtain the appropriate Brodmann area (BA) and anatomic labels.

Multivariate analyses

Multivariate analyses were conducted using PRoNTo, a pattern recognition toolbox for neuroimaging (http://www.mlnl.cs.ucl.ac.uk/pronto, Schrouff et al., 2013). We trained classifiers to distinguish voxel activity patterns associated with RI versus facilitation conditions (for each task domain and age group separately) based on single-trial univariate beta images and using a binary support vector machine (Burges, 1998) for each participant separately. A standard mask removing voxels outside the brain was applied to all images. For within-domain classifications of RI level, a leave-one-subject-per-group-out (LOSO) cross-validation procedure was used, 'subject' meaning here 'trial' given the specific setup based on beta images. For between-domain predictions of RI conditions, a custom cross-validation procedure was used allowing to train the RI-condition classifier on one task domain and to test the classifier on another task domain, resulting in six test-train pairs (see https://osf.io/efmhc/, Grégoire et al., 2023, for details of the cross-validation matrix). At the group level, within-domain and between-domain classifier performance was tested by comparing the group level distribution of classification accuracies to a chance-level distribution using Bayesian one sample t-tests. Finally, data visualizations for the multivariate analyses were performed in R Studio (R 3.3.0) with R (4.03.0), R Core Team, (2019). These scripts are also available on the open repository.

Results

Behavioral Analyses

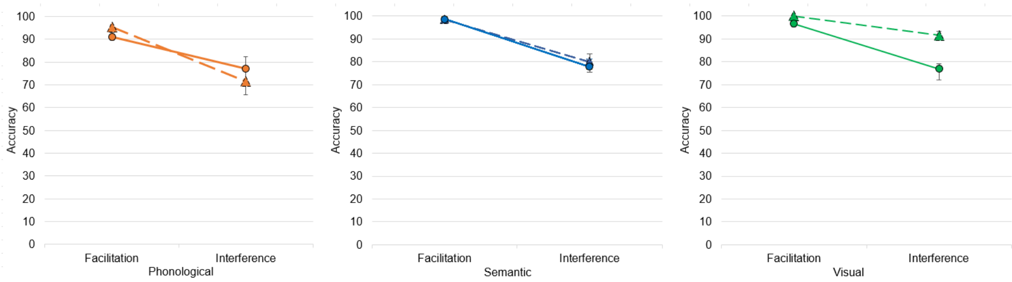
A first 2 (Group: Young adults, Elderly adults) × 2 (Condition: Facilitation, Interference) × 3 (Domain: Phonological, Semantic, Visual) Bayesian mixed

ANOVA was performed on the overall accuracy score. Results are displayed in Figure 2. The model associated with the strongest evidence (BF_{10} = 1.29e+12) included the Domain (η^2_p = .11) and Condition (η^2_p = .60) variables. This model was 2.56 more likely than the second one, which included the same factors as well as the Group factor and the interaction between Domain and Group. As expected, Bayesian post-hoc tests showed that accuracy was higher in the Facilitation condition compared to the RI condition (BF_{10}= 6.29e+10). Post-hoc tests also revealed higher accuracy in the Visual domains compared to the Phonological domain (BF_{10} = 60.98), with slight evidence for a difference between the Semantic and Phonological domains (BF_{10} = 4.00) but no evidence for or against a difference between Visual and Semantic domains (BF_{10} = 0.78; BF_{01} = 1.28).

Another 2 (Group: Young adults, Elderly adults) × 2 (Condition: Facilitation, Interference) × 3 (Domain: Phonological, Semantic, Visual) Bayesian Repeated Measures ANOVA was performed on the response times for correct answers. The results are displayed in Figure 3. The most parsimonious model with the strongest evidence (BF_{10} = 9.53e+24) included the three main factors (Group: η^2_p = .14, Domain: η^2_p = .48, Condition: η^2_p = .64), the interactions between Domain and Condition (η^2_p = .09), Domain and Group (η^2_p = .01), Group and Condition (η^2_p = .15), and the triple interaction (η^2_p = .08). As expected, post-hoc tests showed that the younger adult group was faster to respond compared to the elderly group (BF_{10} = 22.86). The post-hoc tests also showed that responses were faster in the Facilitation condition compared to the RI condition (BF_{10} = 7.34e+10). Furthermore, responses were faster in the Semantic and Visual domains compared to the Phonological domains (BF_{10} = 1.59e+10; BF_{10} = 5.84e+12), with no reliable between the Semantic and Visuals domains (BF_{01} = 2.01). The interaction between Domain and Condition indicates that the interference effect was more pronounced in the phonological task domain relative to the semantic and visual task domains (Phonological: η^2_p = .66; Semantic: η^2_p = .39; Visual: η^2_p = .40). The interaction between Domain and Group shows a slightly stronger domain effect in the young than in the elderly group (Domain effect: Young: η^2_p = .52. Elderly: η^2_p = .46), both groups being slowest for the phonological domain, and young participants furthermore being slower for the semantic as compared to the visual domain while there was no difference between these two domains in the elderly group. The interaction between Group and Condition shows that the elderly group was slightly more impacted by the RI conditions than the younger group (Condition effect: Young: η^2_p = .57; Elderly: η^2_p = .68). Lastly, the triple interaction reveals that the elderly group demonstrated pronounced interference effects in all three domains while the younger group showed a much stronger interference effect in the phonological domain compared to the two other domains (Condition effect, young adults: Phonological: $\eta^2_p = .61$; Semantic: $\eta^2_p = .26$; Visual: $\eta^2_p = .20$; elderly adults: Phonological: $\eta^2_p = .74$; Semantic: $\eta^2_p = .47$; Visual: $\eta^2_p = .52$).

Figure 2

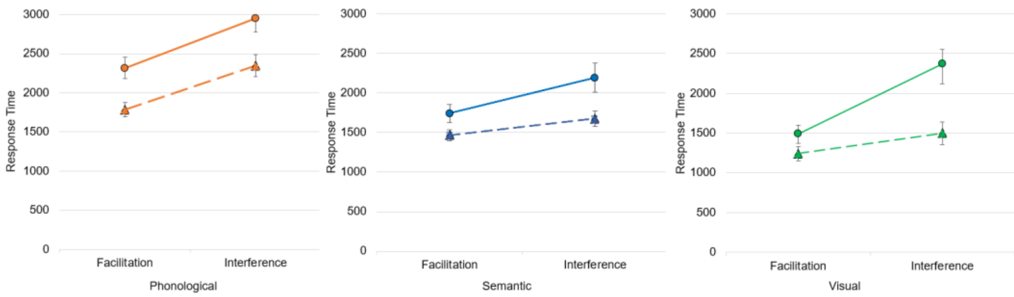
Response Accuracy as a Function of Age Group and Task Domain.



Note. --▲ : Young adults, -● : elderly adults. Horizontal bars indicate standard errors.

Figure 3

Response times as a function of age group and task domain.



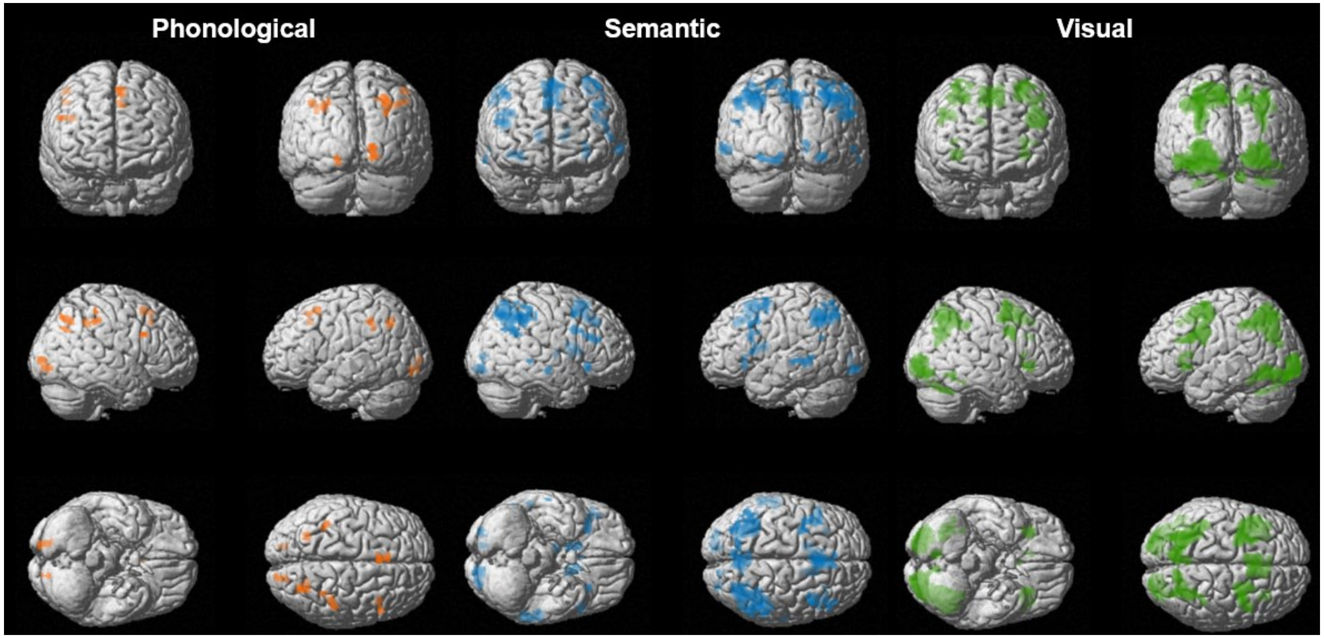
Note. --▲ : Young adults, -● : elderly adults. Horizontal bars indicate standard errors.

Univariate Analyses

A 3 (domains) × 2 (groups) whole-brain voxel-wise ANOVA was performed in order to examine univariate activity peaks associated with RI as a function of task domain (phonological, semantic visual) and age group (young, elderly). The domain effect was associated with activity differences in the right superior frontal gyrus, bilateral inferior and middle frontal gyri, bilateral inferior occipital cortices, bilateral middle temporal gyri, bilateral angular gyri, and the left intraparietal sulcus (see Table 2). The domain effect was explored first by examining activity associated with RI within each domain separately by performing a null conjunction over relevant contrasts in young and elderly participants (see Figure 4). RI in the phonological domain was associated with activity foci in the right angular gyrus and the right lingual gyrus. RI in the semantic domain was associated with activity foci in bilateral IFG, in the bilateral superior parietal and angular gyri, and in the left middle temporal gyrus. RI in the visual domain was associated with a similar set of regions but included middle and superior frontal gyri and bilateral occipital gyri. When contrasting the different domains (see Table 3), there was more important involvement of the left superior parietal lobule in the visual domain compared to the phonological domain. The main effect of age in the ANOVA analysis revealed clusters of activity differences in the right superior temporal gyrus, the right supramarginal gyrus, the left middle occipital gyrus, and inferior frontal gyri (see Table 2) but age did not significantly interact with domain. Age effects were first explored by determining RI effects within each age group separately and by running a null conjunction over the three domains. RI in the young group was associated with activity foci in the bilateral IFG, as well as in the superior parietal and inferior occipital gyri (see Figure 5). RI effects in the elderly group were associated with activity foci mainly in the right angular and middle/superior occipital gyri. However, when contrasting the two groups (by running a null conjunction analysis over the three domains), no significant activity differences between the two groups were revealed, showing that there were no robust age effects across the three domains.

Figure 4

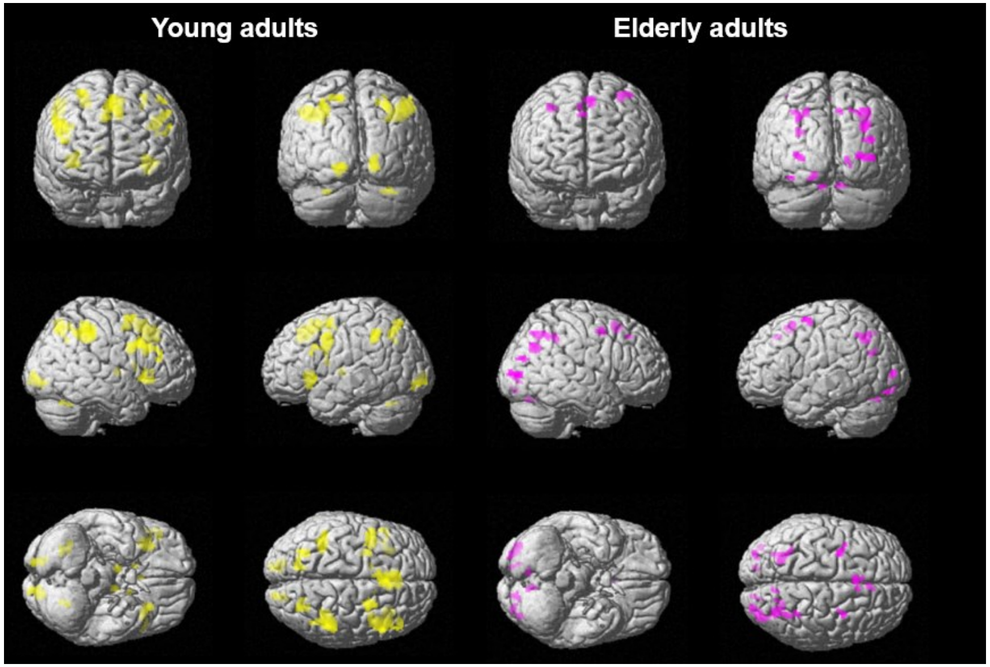
Univariate Activity Peaks for RI vs. Facilitation Condition Contrasts, as a Function of Task Domain.



Note. Regions are displayed at an uncorrected voxel-level threshold of P <.001, based on null conjunctions over relevant contrasts (RI > facilitation) in the two age groups, with a minimum cluster size of 10 voxels.

Figure 5

Univariate activity peaks for RI vs. facilitation condition contrasts, as a function of age group



Note. Regions are displayed at an uncorrected voxel-level threshold of P <.001, based on null conjunctions over relevant contrasts (RI > facilitation) in the three task domains, with a minimum cluster size of 10 voxels.

Table 2
Univariate results for group and task domain effects on RI contrasts and their interaction (ANOVA).

Anatomical regions	ANOVA							
	BA area	No. Voxels (k > 10)	Left / Right	x	y	z	SPM {Z}-value for peak-level	*F*
Main effect of Domain,		FWEc: *k* ≥ 53						*F(2,183)*
Superior frontal gyrus	8	67	R	44	10	48	4.97	16.22
Middle frontal gyrus	6	186	R	26	2	50	4.46	13.30
Middle frontal gyrus	6	224	L	-26	2	50	4.45	13.25
Medial frontal gyrus	6	245	L	-2	12	52	4.52	13.59
Inferior frontal gyrus	44/6	53	R	50	2	4	4.15	11.71
	44/13	66	R	32	26	-2	4.29	12.39
Pars opercularis	44	105	R	42	10	36	4.20	11.93
Inferior frontal gyrus	44	79	L	-32	24	-4	4.49	13.44
Pars opercularis	44	100	L	-34	12	28	5.03*	16.53
			L	-16	16	32	4.63*	14.21
			L	-40	12	32	4.58	13.92
Pars triangularis	44	132	L	-42	18	28	5.35*	18.59
			L	-36	14	28	5.05	14.71
Angular gyrus	39	1081	R	60	-56	24	5.58	20.12
			R	54	-46	38	5.20	17.65
			R	56	-58	36	5.13	17.16
			R	62	-52	22	5.11	17.05
			R	52	-54	24	5.03	16.55
			R	46	-50	20	4.94	16.00
Angular gyrus	39	133	L	-48	-56	38	5.13	17.17
Middle temporal gyrus	21	231	R	64	-18	-12	5.54	19.88

			R	62	-30	-6	5.00	16.36
Middle temporal gyrus	21	130	L	-50	-40	4	4.55	13.76
	21	67	L	-58	-28	-4	4.45	13.25
Intraparietal sulcus	7	1709	L	-28	-58	48	5.30	18.29
			L	-28	-72	42	4.98	16.23
Precuneus	7	59	R	30	-66	36	4.14	11.64
Inferior occipital gyrus	18	718	L	-30	-86	-10	5.53	19.15
			L	-44	-58	-8	4.04	11.14
Inferior occipital gyrus	18	352	R	30	-88	-8	4.65	14.32
Caudate		82	R	14	6	14	4.32	12.55
Main effect of Group,		FWEc: $k \geq 55$						*F(1,183)*
Inferior frontal gyrus								
Pars opercularis	44	18	R	50	16	38	4.10*	19.11
Pars orbitalis	47	23	L	-46	16	-10	4.10*	19.11
			L	-42	18	-4	3.87*	17.11
Precentral gyrus	6	71	R	4	-4	52	4.10	19.11
Superior temporal gyrus	22	55	R	54	-2	4	4.47	22.65
Supramarginal gyrus	40	102	R	46	-38	44	4.93	27.61
Middle occipital gyrus	19	55	L	-42	-80	14	3.93	17.60
Caudate		61	R	12	16	4	3.72	15.85
Interaction Domain x Group, no voxel survived at $p < .05$								*F(2,183)*

Note. If not otherwise stated, regions are significant $p < .05$ at cluster-level FWE corrections for whole-brain volume. * $p < .05$ small volume corrections, for region-of-interest. FWEc: the extent number of voxel threshold, k, defined from a statistical threshold p<.05 for cluster-level inference.

Table 3
Univariate simple effects and between-domain comparisons for RI contrasts

Anatomical regions	BA area	No. Voxels	Left / Right	x	y	z	SPM {Z}-value	*T*
Simple effect of semantic RI[a]		FWEc: *k* ≥ 66						T^2_{183} {Ha:k=2}
Inferior frontal gyrus, *pars orbitalis*	47	77	R	30	22	-10	4.36	4.48
Inferior frontal gyrus, *pars opercularis*	44	140	L	-46	18	22	4.08	4.18
Inferior frontal gyrus, *pars opercularis*	44	126	R	40	14	30	4.04	4.13
Inferior frontal gyrus, *pars triangularis*	9	67	R	46	26	24	4.34	4.44
Superior medial frontal gyrus	6	499		0	14	58	4.92	5.09
Precentral gyrus	6	108	L	-38	2	60	4.35	4.48
Middle temporal gyrus	21	108	L	-66	-38	-2	4.60	4.74
Precuneus	7	327	R	4	-70	48	4.42	4.55
Angular gyrus, Superior parietal lobule	7/39	930	R	34	-68	48	5.62	5.88
			R	44	-48	46	4.95	5.12
Angular gyrus	7/39	567	L	-34	-58	44	4.44	4.57
Inferior occipital gyrus	18	96	L	-14	-92	-12	4.32	4.44
Caudate		93	L	-14	6	14	5.26	5.47
Caudate		137	R	12	8	14	5.17	5.37
Simple effect of phonological RI[a]		FWEc: *k* ≥ 66						T^2_{183} {Ha:k=2}
Lingual gyrus, cuneus	37	87	R	18	-86	-6	4.18	4.29
Angular gyrus	40	66	R	-28	-68	44	3.65	3.73
Simple effect of visual RI[a]		FWEc: *k* ≥ 94						T^2_{183} {Ha:k=2}
Inferior frontal gyrus, *pars opercularis*	44/13	133	R	34	26	-2	4.59	4.73
Inferior frontal gyrus, *pars opercularis*	44/13	149	L	-30	24	0	4.46	4.59
Inferior frontal gyrus, *pars triangularis*	45	158	L	-44	18	28	4.87*	5.03
Middle frontal gyrus	6	953	L	-26	-4	52	5.10	5.30
			L	-46	16	30	4.99	5.17

Middle frontal gyrus	6	278	R	26	-2	48	4-92	5.09
Medial frontal gyrus	6	461	L	-2	14	52	5.13	5.33
Superior frontal gyrus, frontal eye field	8	133	R	46	8	34	4.51	4.65
Superior parietal lobule	7	1540	L	-30	-58	46	5.68	5.94
			L	-28	-68	32	5.11	5.30
Precuneus	7	715	R	30	-66	34	5.29	5.50
			R	32	-58	48	4.61	4.75
Inferior occipital gyrus	18	94	R	34	-60	-28	4.65	4.80
Inferior occipital gyrus	18	1349	L	-30	-84	-12	5.49	5.73
			L	-26	-94	-8	5.08	5.27
Middle occipital gyrus	18	615	R	18	-86	-8	5.00	5.18
Cross-domain RI in Young Adults[b]		FWEc: $k \geq 68$						T^3_{183} {Ha:k=3}
Inferior frontal gyrus, *pars opercularis*	44	221	R	46	10	34	4.54	4.68
Superior frontal gyrus, frontal-eye-field	8	337	L	-4	22	44	4.26	4.38
Inferior Precentral gyrus	6	143	L	-42	4	34	4.26	4.37
Superior Precentral gyrus	6	100	R	28	8	62	3.91	4.00
Intraparietal sulcus		181	L	-40	-46	40	4.42	4.55
Suparmarginal gyrus	40	352	R	46	-36	44	5.60	5.85
Superior parietal lobule	7	68	L	-28	-66	48	4.14	4.24
Superior parietal lobule	7	102	R	30	-72	48	4.21	4.32
Inferior occipital gyrus	18	94	R	18	-90	-6	4.28	4.39
Inferior occipital gyrus	18	119	L	-12	-92	-8	4.13	4.23
Insula	13/44	158	R	36	18	-2	4.47	4.60
Insula	13/44	86	L	-30	26	0	4.11	4.21
Cross-domain RI in Elderly adults[b]		FWEc: $k \geq 72$						T^3_{183} {Ha:k=3}
Angular gyrus	39	72	R	32	-68	32	4.31	4.43
Middle occipital gyrus	18	78	R	36	-84	4	4.17	4.28
Superior occipital gyrus	19/39	93	R	34	-58	46	4.04	4.13

Superior parietal lobule	7	76	L	-22	-64	46	3.95	4.04
Phonological RI > Semantic RI, no voxel survived.								
Phonological RI > Visual RI, no voxel survived.								
Semantic RI > Phonological RI								
Semantic RI > Visual RI, no voxel survived.								
Visual RI > Semantic RI, no voxel survived.								
Visual RI > Phonological RI		FWEc: $k \geq 120$						T^2_{183} {Ha:k=2}
Superior parietal lobule	7	120	L	-28	-58	48	4.12	4.22
Young > Elderly, no voxel survived.								
Elderly > Young, no voxel survived.								

Note. If not otherwise stated, regions are significant $p < .05$ at cluster-level FWE corrections for whole-brain volume. * $p < .05$ with small volume corrections for ROIs. FWEc: the extent number of voxel threshold, k, defined from a statistical threshold p<.05 for cluster-level inference. a: null conjunction over relevant contrasts in young and elderly participants. b: null conjunction over relevant contrasts in phonological, semantic, and visual domains.

Multivariate analyses

Whole-Brain Multivariate Classifications Analyses

A first set of multivariate analyses assessed between-condition (RI vs. facilitation) classifications within each task domain at the whole-brain level. By performing Bayesian one-sample t-test, we observed reliable classification of the RI vs. facilitation conditions for each group and each task domain (see Figure 6 and Table 4; phonological: BF_{10} = 712763 for young adults, BF_{10} = 9854.01 for elderly adults; semantic : BF_{10} = 1.36e+6 for young adults, BF_{10} = 30244.35 for elderly adults; visual domain: BF_{10} = 1.72e+7 for young adults, BF_{10} = 4.40e+7 for elderly adults). These results were further explored via a 3 (domain) x 2 (group) Bayesian mixed ANOVA, showing that the model associated with the strongest evidence (BF_{10} = 10.21) included the Domain main effect (η^2_p = .09), indicating slightly higher classification in the visual task domain (see Figure 4), and evidence for the *absence* of a group effect (BF_{01} = 4.79); the group-by-domain interaction (BF_{01} = 6.87) was also characterized by evidence for the null.

Regions-of-Interest Multivariate Classifications Analyses

Next, we determined the extent to which these classifications are driven by the different ROIs in the right and left IFG: the pars orbitalis, the pars triangularis, and the pars opercularis. All ROIs were associated with reliable classification in both groups for all task domains ($BF_{10} > 37$ for the young adults; $BF_{10} >12$ for the elderly adults) except for the right IFG pars orbitalis when examining classifications in the semantic domain for the elderly group (BF_{10} = 1.56; BF_{01} = 0.64), see Table 4 and Figure 7. When performing a 3 (domain) x 2 (hemisphere) x 2 (group) ANOVA on each ROI, all effects were associated with evidence for the null, indicating the absence of a modulation of the classifications in the different ROIs by task domain, group, or hemisphere ($BF_{10} < 1$; $BF_{01} > 1.5$). The Bayesian model comparison tables are displayed in the Supplementary Data file.

Table 4

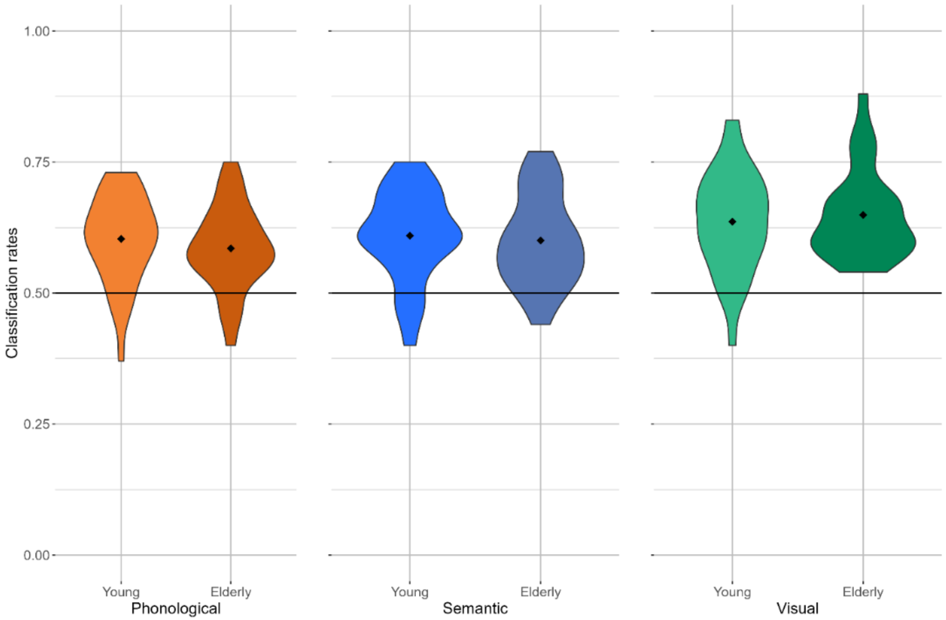
Bayesian One-Sample T-Test values for the within-domain classification of RI vs. facilitation conditions in young and elderly adults at the whole-brain and ROI levels

	Domain	Young	Elderly
		BF_{10}	BF_{10}
Whole-Brain			
	Visual	**1.72e+7**	**4.40e+7**
	Phonological	**712763.30**	**9854.01**
	Semantic	**1.36e+6**	**30244.35**
Pars Triangularis			
Left	Visual	**32249.50**	**1675.04**
	Phonological	**315.10**	**131.22**
	Semantic	**3134.80**	**78.00**
Right	Visual	**142.76**	**47301.85**
	Phonological	**162.02**	**48.67**
	Semantic	**1948.24**	**12.75**
Pars Orbitalis			
Left	Visual	**439.36**	**193.11**
	Phonological	**37.43**	**24.70**
	Semantic	**1.95e+6**	**39.60**
Right	Visual	**180.05**	**32470.13**
	Phonological	**230.00**	**30.88**
	Semantic	**2000.19**	1.56
Pars Opercularis			
Left	Visual	**2113.47**	**21852.69**
	Phonological	**44.44**	**77.68**
	Semantic	**331.88**	**40.03**
Right	Visual	**801.73**	**6173.44**
	Phonological	**8459.68**	**38.29**
	Semantic	**503.19**	**1317.32**

Note. For all tests, the alternative hypothesis (H_1) specifies that the population mean is greater than above-chance level classification. BF_{10} values larger than 3 are flagged in bold font.

Figure 6

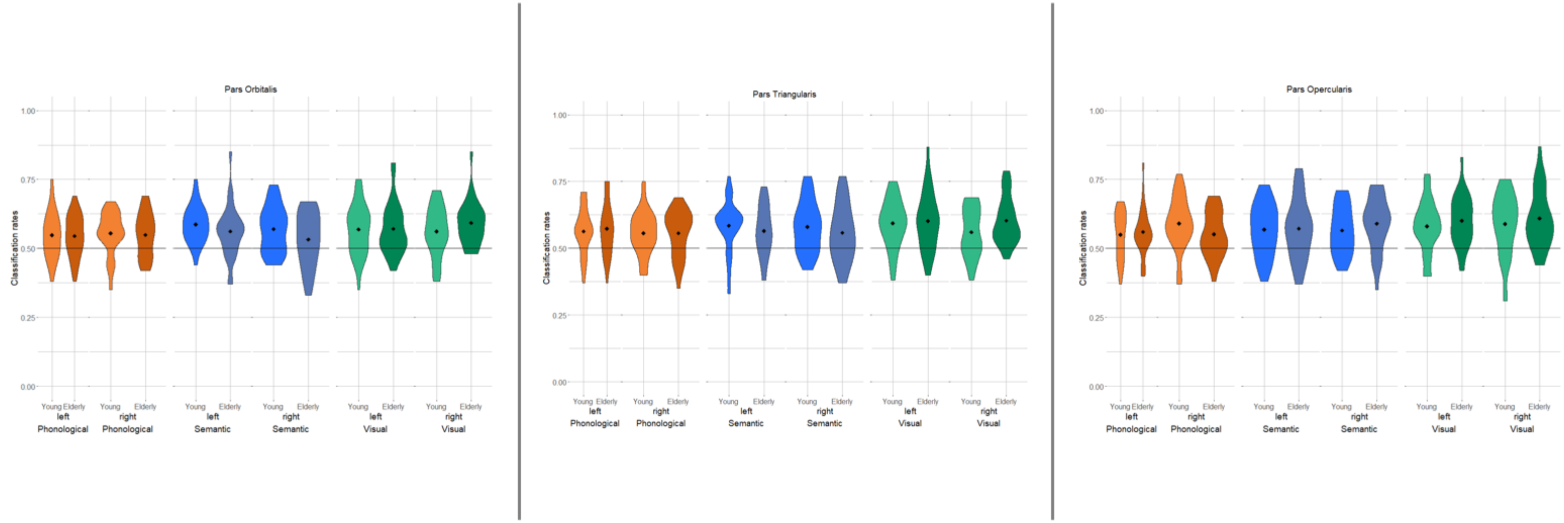
Classification rates for RI vs. facilitation conditions, as a function of age group and task domain.



Note. The black line marks chance-level classification rates (0.5, 50%). Vivid orange: young adults; Dark orange: elderly adults; Vivid Blue: young adults; Dark blue: elderly adults; Vivid Green: young adults; Dark green: elderly adults.

Figure 7

Classification rates for RI vs. facilitation conditions, as a function of group, ROI, and type of domain.



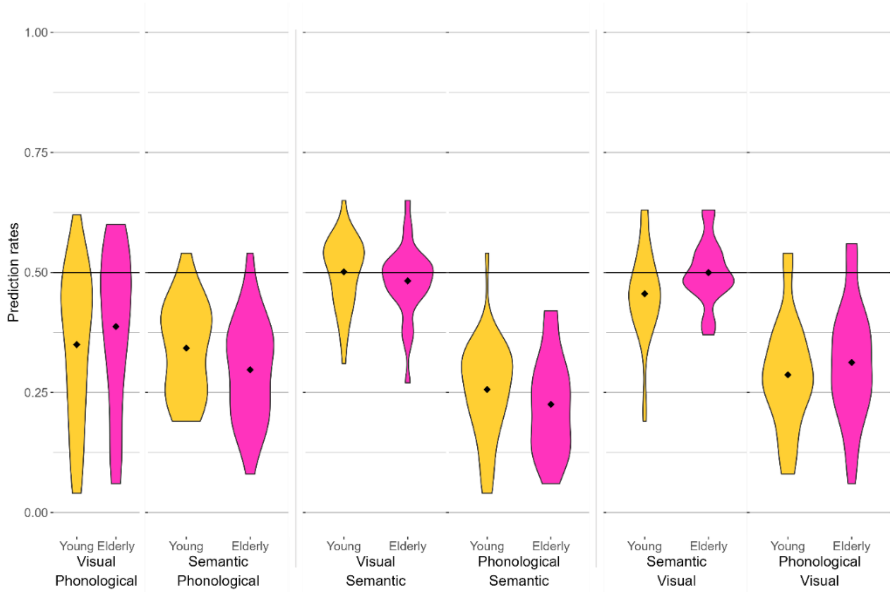
Note. From left to right: Pars Orbitalis Pars Triangularis, and Pars Opercularis. Vivid orange: young adults; Dark orange: elderly adults; Vivid Blue: young adults; Dark blue: elderly adults; Vivid Green: young adults; Dark green: elderly adults. Each mean is plotted with a black point. The black line marks chance-level classification rate (0.5, 50%).

Multivariate Between-Domains Predictions Analyses

Next, we proceeded to the critical between-domain predictions of the RI conditions, by training the condition classifier in one task domain and by testing the classifier on the other task domains in a pairwise manner (training in one domain and prediction on one other domain, by repeating this procedure for all possible pairings, see Method section). When running these analyses at the whole-brain level, we obtained reliable evidence for an *absence* of between-task predictions for all pairings and in each group (BF_{01} = [5.07 to 162.93]), see Table 5 and Figure 8. The same results were obtained when running the same analysis on the three ROIs (BF_{01} = [1.46 to 181.44]), except for two above-chance level predictions in the young adult group involving the left pars orbitalis (BF_{10} = 7.36) and the left pars triangularis (BF_{10} = 9.47) for the prediction of RI condition from the visual to the semantic task domain. Similar, although less reliable results, were also observed for the elderly group (BF_{10} = 2.37 and 2.08).

Figure 8

Prediction rates from one task domain on the other task domains at the whole-brain level, as a function of age group.



Note. The black line marks chance-level classification rates (0.5, 50%). Yellow: young adults; Pink: Elderly adults.

Figure 9

Prediction rates from one task domain (bottom legend) on the other task domains (middle legend) in the three ROIs, as a function of age group (upper legend) and Hemispheres (left ROIs on the left, right ROIs on the right).

Note. The black line marks chance-level classification rates (0.5, 50%). Yellow: young adults; Pink: Elderly adults.

Table 5

Bayesian One-Sample T-Tests for between-domain predictions of RI vs. facilitation conditions in young and elderly adults at the whole-brain and ROI levels.

	Domain (trained → predicted)		Young	Elderly
			BF_{01}	
Whole-Brain				
	Phonological	→ Visual	**52.63**	**20.15**
	Visual	→ Phonological	**120.57**	**79.92**
	Semantic	→ Visual	**5.25**	**10.41**
	Visual	→ Semantic	**17.92**	**5.07**
	Phonological	→ Semantic	**99.23**	**102.82**
	Semantic	→ Phonological	**162.93**	**153.18**
Pars Triangularis				
Left	Phonological	→ Visual	**16.72**	**16.93**
	Visual	→ Phonological	**100.36**	**59.24**
	Semantic	→ Visual	**18.23**	**12.37**
	Visual	→ Semantic	0.11 #	0.48
	Phonological	→ Semantic	**135.50**	**111.38**
	Semantic	→ Phonological	**181.44**	**168.81**
Right	Phonological	→ Visual	**17.30**	**17.06**
	Visual	→ Phonological	**25.94**	**16.92**
	Semantic	→ Visual	**11.53**	**8.97**
	Visual	→ Semantic	2.06	**8.01**
	Phonological	→ Semantic	**80.12**	**88.11**
	Semantic	→ Phonological	**89.50**	**106.74**
Pars orbitalis				
Left	Phonological	→ Visual	**17.91**	**9.64**
	Visual	→ Phonological	**67.79**	**21.90**
	Semantic	→ Visual	**10.19**	**9.65**
	Visual	→ Semantic	0.14 #	**0.35**
	Phonological	→ Semantic	**125.21**	**96.12**
	Semantic	→ Phonological	**146.12**	**99.18**
Right	Phonological	→ Visual	**8.14**	**8.45**
	Visual	→ Phonological	**20.70**	**20.81**
	Semantic	→ Visual	**13.95**	**10.33**
	Visual	→ Semantic	1.46	**2.96**
	Phonological	→ Semantic	**47.61**	**61.54**
	Semantic	→ Phonological	**24.97**	**80.95**
Pars opercularis				
Left	Phonological	→ Visual	**22.76**	**21.54**
	Visual	→ Phonological	**92.68**	**61.66**
	Semantic	→ Visual	**17.65**	**9.67**

	Visual	→ Semantic	1.57	0.42
	Phonological	→ Semantic	**80.72**	**111.37**
	Semantic	→ Phonological	**119.45**	**119.86**
Right	Phonological	→ Visual	**12.44**	**6.22**
	Visual	→ Phonological	**13.81**	**10.13**
	Semantic	→ Visual	**6.37**	**10.69**
	Visual	→ Semantic	2.33	**6.27**
	Phonological	→ Semantic	**101.31**	**94.37**
	Semantic	→ Phonological	**100.37**	**114.99**

Note. For all tests, the alternative hypothesis (H_1) specifies that the population mean is greater than above-chance level classification. Note that the table reports BF_{01} values, representing evidence for an *absence* of above-chance-level classification. BF_{01} values larger than 3 are flagged in bold font. # indicates $BF_{10} > 3$.

Discussion

This study examined the commonality of univariate and multivariate neural substrates associated with RI in phonological, semantic, and visual domains for young and elderly healthy participants. By using structurally equivalent similarity-judgement paradigms for measuring RI in the three domains, we observed, at the univariate neural level, a main effect of RI domain, with activity differences in the bilateral IFG, inferior occipital cortices, middle temporal gyri, angular gyrus, and intraparietal sulcus. The main effect of age was associated with activity differences in the angular, supramarginal, and inferior frontal gyri, but did not interact with domain and was not confirmed when directly contrasting the two groups across the three domains via a null conjunction test. Critically, at the multivariate level, although RI vs. facilitation conditions could be decoded in the IFG ROIs for all domains, between-domain prediction of RI vs. facilitation condition was associated with evidence for the null, both at the level of whole-brain and ROI analyses.

The domain-specific vs. domain-general nature of RI processes

The univariate results suggest that RI in different task domains (phonological, semantic visual) is associated with modality-specific neural substrates, despite common involvement of the left IFG at least in young adults. Regarding RI in the semantic domain , the (stronger) recruitment of the IFG, middle temporal gyri (MTG), and angular gyrus (AG) may reflect domain-specific processes related to semantic processing and control. The bilateral IFG, the MTG as well as the AG have been associated in previous studies with verbal (semantic) control (Attout et al., 2022; Badre & Wagner, 2005; Binder et al., 2009; Davey et al., 2016; Jefferies et al., 2020; Jefferies & Lambon Ralph, 2006b; Noonan et al., 2010; Ralph et al., 2016; Rodd et al., 2005; Seghier et al., 2010; Thompson-Schill et al., 1999). For phonological RI, we observed involvement of the right lingual gyrus and right AG but none of these regions showed specific differential involvement when directly contrasting the domains. Regarding visual RI, the left superior lobule and inferior occipital gyri showed specific activity increases. These regions have been associated with visual attentional control processes (Corbetta & Shulman, 2002, 2011; Majerus et al., 2018). The multivariate results provide further critical support for a domain-specific view of RI processes. Although within-domain classifications showed reliable decoding of RI conditions in the left and right IFG across the three conditions and all ROIs, between-domain classifications of RI conditions were associated with clear evidence for the null, suggesting that the multivariate patterns that characterize RI in the different IFG ROIs differ as a function of task domain. Note however that some limited evidence for between-domain prediction was observed in the young adult group, with above-chance-level prediction from the visual to the semantic domain in two out of six ROIs, indicating some similarity in neural patterns during RI resolution for visual and semantic information. This result should however not be over-interpreted as the reverse prediction (semantic → visual) was associated with evidence for the null hypothesis.

Our results are in line with other studies suggesting domain-specific RI processes (Attout et al., 2022; Morimoto et al., 2008; Schumacher et al., 2011; Stephan et al., 2003) but go significantly beyond these studies by comparing a broader set of domains and, critically, by using carefully matched tasks for probing between-domain specificities and similarities in RI. In earlier studies, the neural specificities observed for RI as a function of domain could have been determined, at least partially, by the, sometimes, important differences between tasks used for assessing RI in specific domains. Importantly, our results also reveal that the neural domain-specificity of RI is age-invariant, at least when examining young and elderly adult populations. Interestingly, our data are also in agreement with previous studies that have highlighted common involvement of the IFG in RI across domains (Funahashi, 2022; Kadota et al., 2010; S. Martin et al., 2006; Nathaniel-James, 2002; Snyder et al., 2007) in the sense that they show that univariate neural signals in the IFG are involved in RI for semantic, phonological and visual domains.

Critically, however, our results are the first to show that the multivariate signals in the IFG, although distinguishing RI from non-RI conditions in all three domains, do so in a domain-specific manner. This important result is also compatible with recent computational models of cognitive control, considering that cognitive control is defined by a task-specific neural adaptations between prefrontal and posterior modality-specific cortices (Verbeke & Verguts, 2021; Verguts, 2017b)

RI and aging

At the behavioral level, we demonstrated that elderly adults exhibited overall slower response times compared to younger adults, in line with age-related changes in processing speed and theoretical frameworks considering that processing speed is one of the first cognitive domains to show age-related decline (Salthouse, 1996b). Furthermore, the group by condition interactions indicates that the elderly group was disproportionately affected by the RI condition. This is in line with previous studies showed age-related increased for response times during RI resolution (Collette, Germain, et al., 2009; Collette, Schmidt, et al., 2009; see Augustinova et al., 2018; Burke & Osborne, 2007 for reviews) . Critically, however, there were no reliable differences in RI accuracy between the two age groups. These results indicate that the ability to inhibit interfering information remains relatively intact in the age group tested in this study at least in terms of erroneous responses (see also Rey-Mermet & Gade, 2018; Verhaeghen & De Meersman, 1998ab).

The absence of age effects in accuracy is also in line with our multivariate results, showing that the neural differentiation of RI and facilitation conditions was similar in both age groups. Also, although the ANOVA for univariate results indicated possible age effects in the RI condition, direct univariate contrasts could not confirm cross-domain age-related differences in activity peaks in the IFG or other areas. It has been suggested that age effects on the brain may be modulated by the specific characteristics of the participants such as proposed by the Brain Maintenance theory (Nyberg et al., 2012) and the Scaffolding Theory of Aging and Cognition-revised (Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014); see McDonough et al., 2022 for a review). These theories consider that life-course experience, either positive (e.g., high level of education, physical activity, social gatherings, …) or negative (e.g., stressful environment, lacking resources or security, …) can maintain or deteriorate cognitive and brain reserve. In the present case, participants of this study were all characterized by high levels of education and also high MoCA scores (mean > 27; cut-off: 23) the latter being known for their dependency on educational level (Malek-Ahmadi et al., 2015; Y. Wu et al., 2023). The absence of reliable age effects on RI, at least in terms of accuracy , could thus be related to the neuroprotective effects associated with high educational status of our participants.

One final question we need to address concerns the sensitivity of the different domains for eliciting interference. Regarding the task demands, the RI condition effect was stronger in phonological than in the two other domains (66%, 39% and 40%, respectively) and the triple interaction for reaction times showed that this was particularly the case for the young participant group. These differences are not likely to stem from sensory aspects of the tasks, at least for the phonological vs. semantic tasks, as prime stimuli were presented auditorily, and target/test stimuli were presented visually in both task domains. A factor that may explain the increased RI effect in the phonological task may be related to the low familiarity of the stimuli (nonwords) for the phonological task, relative to the words and basic visual features used in the other two tasks. At the same time, this situation is not likely to have had a significant impact on neural results given that no increased univariate RI effects were observed for the phonological task when directly contrasted to the semantic or the visual tasks. Indeed, the conjunction analyses mainly revealed increased activity peaks for the semantic and visual domains rather than the phonological domain.

Conclusions

This study provides novel evidence for the domain-specificity and age-independency of neural substrates associated with RI while reconciling studies that have shown either domain-specific or domain-general involvement of the IFG in RI. This study stresses the importance of using both univariate and multivariate analyses techniques to allow for a full appreciation of the nature of IFG involvement in RI across different domains.

Supplementary Data

Table 1
Descriptives Data

	Group	N	Mean	SD	SE	Coefficient of variation	95% Credible Interval	
							Lower	Upper
Etudes	1	34	15.44	1.96	0.34	0.13	14.76	16.12
	2	29	14.97	1.80	0.33	0.12	14.28	15.65
Age	1	34	25.09	3.72	0.64	0.15	23.79	26.39
	2	29	67.55	5.47	1.02	0.08	65.47	69.63
Mill Hill	1	34	24.47	2.87	0.49	0.12	23.47	25.47
	2	29	29.31	2.88	0.53	0.10	28.21	30.41
MoCA	1	0	NaN				NaN	NaN
	2	28	27.25	1.84	0.35	0.07	26.54	27.96

Table 2

Descriptive data for Accuracy in terms of Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference) and Groups (Young, Elderly) for the Similarity-Judgement Task.

						95% Credible Interval	
Domains	**Conditions**	**Groups**	**Mean**	**SD**	**N**	**Lower**	**Upper**
Phonoloical	Facilitation	1	95.48	3.96	34	94.09	96.86
		2	91.11	9.08	29	87.66	94.57
	Interference	1	71.49	34.32	34	59.52	83.47
		2	77.19	28.07	29	66.51	87.87
Semantic	Facilitation	1	98.53	3.14	34	97.43	99.63
		2	98.67	2.77	29	97.62	99.73
	Interference	1	79.98	19.54	34	73.16	86.79
		2	77.85	12.32	29	73.17	82.54
Visual	Facilitation	1	100.00	0.00	34	100.00	100.00
		2	96.68	8.14	29	93.59	99.78
	Interference	1	91.52	10.83	34	87.74	95.29
		2	76.92	26.86	29	66.70	87.14

Table 3
Model comparison for Bayesian Repeated Measures ANOVA conducted on Accuracy with Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference) and Groups (Young, Elderly) for the Similarity-Judgement Task.

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject and random slopes)	0.05	2.87e-13	5.17e-12	1.00	
Domains + Conditions	0.05	0.37	10.54	1.29e+12	1.46
Domains + groups + Conditions + Domains ✻ groups	0.05	0.14	3.04	5.03e+11	2.68
Domains + groups + Conditions	0.05	0.14	3.03	5.02e+11	2.76
Domains + Conditions + Domains ✻ Conditions	0.05	0.11	2.14	3.70e+11	6.55
Domains + groups + Conditions + Domains ✻ groups + Domains ✻ Conditions + groups ✻ Conditions + Domains ✻ groups ✻ Conditions	0.05	0.05	0.93	1.72e+11	4.31
Domains + groups + Conditions + Domains ✻ groups + Domains ✻ Conditions	0.05	0.05	0.87	1.60e+11	10.39
Domains + groups + Conditions + Domains ✻ Conditions	0.05	0.04	0.73	1.37e+11	4.30
Domains + groups + Conditions + groups ✻ Conditions	0.05	0.03	0.59	1.11e+11	3.26
Domains + groups + Conditions + Domains ✻ groups + groups ✻ Conditions	0.05	0.03	0.58	1.08e+11	2.99
Conditions	0.05	0.01	0.26	5.01e+10	1.51
Domains + groups + Conditions + Domains ✻ groups + Domains ✻ Conditions + groups ✻ Conditions	0.05	9.95e-3	0.18	3.47e+10	11.80
Domains + groups + Conditions + Domains ✻ Conditions + groups ✻ Conditions	0.05	7.84e-3	0.14	2.73e+10	2.16
groups + Conditions	0.05	5.35e-3	0.10	1.87e+10	1.74
groups + Conditions + groups ✻ Conditions	0.05	1.23e-3	0.02	4.28e+9	5.56
Domains	0.05	6.76e-12	1.22e-10	23.56	1.09
Domains + groups + Domains ✻ groups	0.05	2.76e-12	4.97e-11	9.61	10.23

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Domains + groups	0.05	2.68e-12	4.83e-11	9.35	3.79
groups	0.05	1.08e-13	1.94e-12	0.38	1.49

Note. All models include subject, and random slopes for all repeated measures factors.

Table 4
Descriptive data for Response Times in terms of Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference) and Groups (Young, Elderly) for the Similarity-Judgement Task

						95% Credible Interval	
Domains	**Conditions**	**groups**	**Mean**	**SD**	**N**	**Lower**	**Upper**
Phonoloical	Facilitation	1	1787.39	529.70	33	1599.57	1975.22
		2	2315.45	728.66	28	2032.90	2597.99
	Interference	1	2350.51	805.26	33	2064.97	2636.04
		2	2947.76	886.69	28	2603.94	3291.58
Semantic	Facilitation	1	1466.53	388.70	33	1328.70	1604.36
		2	1740.16	588.85	28	1511.83	1968.49
	Interference	1	1675.50	558.27	33	1477.54	1873.45
		2	2192.90	987.03	28	1810.17	2575.64
Visual	Facilitation	1	1240.55	518.53	33	1056.69	1424.41
		2	1490.55	631.09	28	1245.84	1735.26
	Interference	1	1499.88	818.41	33	1209.69	1790.08
		2	2369.10	1327.37	28	1854.40	2883.80

Table 5

Model comparison for Bayesian Repeated Measures ANOVA conducted on Response Times with Domains (Phonological, Semantic, Visual), Conditions (Facilitation, Interference) and Groups (Young, Elderly) for the Similarity-Judgement Task.

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject and random slopes)	0.05	4.46e-29	8.03e-28	1.00	
Domains + groups + Conditions + Domains ✻ groups + Domains ✻ Conditions + groups ✻ Conditions + Domains ✻ groups ✻ Conditions	0.05	0.52	19.71	1.17e+28	5.13
Domains + groups + Conditions + Domains ✻ Conditions + groups ✻ Conditions	0.05	0.30	7.55	6.63e+27	3.82
Domains + groups + Conditions + Domains ✻ groups + Domains ✻ Conditions + groups ✻ Conditions	0.05	0.08	1.56	1.79e+27	11.69
Domains + groups + Conditions + groups ✻ Conditions	0.05	0.05	0.93	1.11e+27	3.14
Domains + groups + Conditions + Domains ✻ Conditions	0.05	0.03	0.48	5.83e+26	4.93
Domains + groups + Conditions + Domains ✻ groups + groups ✻ Conditions	0.05	0.01	0.21	2.60e+26	3.88
Domains + groups + Conditions + Domains ✻ groups + Domains ✻ Conditions	0.05	6.64e-3	0.12	1.49e+26	8.44
Domains + groups + Conditions	0.05	4.51e-3	0.08	1.01e+26	3.07
Domains + Conditions + Domains ✻ Conditions	0.05	2.47e-3	0.04	5.53e+25	26.93
Domains + groups + Conditions + Domains ✻ groups	0.05	9.86e-4	0.02	2.21e+25	3.34
Domains + Conditions	0.05	3.80e-4	6.85e-3	8.53e+24	5.57
Domains + groups	0.05	1.71e-13	3.07e-12	3.83e+15	2.56
Domains + groups + Domains ✻ groups	0.05	3.99e-14	7.18e-13	8.94e+14	4.94
Domains	0.05	1.32e-14	2.38e-13	2.97e+14	1.78
groups + Conditions + groups ✻ Conditions	0.05	1.65e-16	2.97e-	3.70e+12	4.51

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
			15		
groups + Conditions	0.05	1.68e-17	3.02e-16	3.76e+11	7.92
Conditions	0.05	1.24e-18	2.22e-17	2.77e+10	2.32
groups	0.05	5.58e-28	1.00e-26	12.50	4.77

Note. All models include subject, and random slopes for all repeated measures factors.

Table 6

Descriptive Data for Bayesian Repeated Measures ANOVA conducted on between-conditions classifications function of Domains (Phonological, Semantic, Visual) and Groups (Young, Elderly)

Descriptives

					95% Credible Interval	
Domains	**groups**	**Mean**	**SD**	**N**	**Lower**	**Upper**
Visual	1	0.64	0.10	34	0.60	0.67
	2	0.65	0.09	29	0.62	0.68
Phonological	1	0.61	0.09	34	0.58	0.64
	2	0.58	0.08	29	0.55	0.62
Semantic	1	0.35	0.16	34	0.29	0.40
	2	0.60	0.09	29	0.57	0.63

Table 7
Model comparison for Bayesian Repeated Measures ANOVA conducted on between-conditions classifications function of Domains (Phonological, Semantic, Visual) and Groups (Young, Elderly)
Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{10}	error %
Null model (incl. subject and random slopes)	0.20	0.07	0.31	1.00	
Domains	0.20	0.74	11.29	10.29	2.66
Domains + groups	0.20	0.15	0.72	2.14	3.36
Domains + groups + Domains ✻ groups	0.20	0.02	0.09	0.31	4.68
groups	0.20	0.01	0.06	0.20	0.72

Note. All models include subject, and random slopes for all repeated measures factors.

Table 8

Descriptive Data for Bayesian Repeated Measures ANOVA conducted on between-conditions classifications function of Domain (Phonological, Semantic, Visual), Group (Young, Elderly), and Hemispheres (Left, Right) in the Pars Triangularis.

						95% Credible Interval	
Domains	**Hemispheres**	**groups**	**Mean**	**SD**	**N**	**Lower**	**Upper**
Visual	Right	1	0.56	0.09	34	0.53	0.59
		2	0.60	0.09	29	0.57	0.64
	Left	1	0.59	0.09	34	0.56	0.62
		2	0.60	0.11	29	0.56	0.64
Phonological	Right	1	0.56	0.08	34	0.53	0.58
		2	0.56	0.08	29	0.52	0.59
	Left	1	0.56	0.09	34	0.53	0.59
		2	0.57	0.10	29	0.53	0.61
Semantic	Right	1	0.58	0.09	34	0.55	0.61
		2	0.56	0.11	29	0.52	0.60
	Left	1	0.58	0.10	34	0.55	0.62
		2	0.56	0.09	29	0.53	0.60

Table 8
Model comparison for Bayesian Repeated Measures ANOVA conducted on between-conditions classifications function of Domain (Phonological, Semantic, Visual), Group (Young, Elderly), and Hemispheres (Left, Right) in the Pars Triangularis.

Models	**P(M)**	**P(M|data)**	**BF_M**	**BF_{01}**	**error %**
Null model (incl. subject and random slopes)	0.05	0.38	10.94	1.00	
Hemispheres	0.05	0.17	3.68	2.23	3.55
Domains	0.05	0.15	3.24	2.48	0.83
groups	0.05	0.09	1.80	4.15	1.64
Domains + Hemispheres	0.05	0.07	1.28	5.68	1.50
Domains + groups	0.05	0.05	0.88	8.07	13.28
Hemispheres + groups	0.05	0.04	0.74	9.57	2.66
Domains + Hemispheres + groups	0.05	0.02	0.30	23.41	1.79
Domains + groups + Domains ✻ groups	0.05	0.01	0.25	27.49	1.70
Hemispheres + groups + Hemispheres ✻ groups	0.05	8.26e-3	0.15	45.74	4.03
Domains + Hemispheres + groups + Domains ✻ groups	0.05	6.14e-3	0.11	61.56	1.89
Domains + Hemispheres + Domains ✻ Hemispheres	0.05	4.61e-3	0.08	82.09	1.85
Domains + Hemispheres + groups + Hemispheres ✻ groups	0.05	3.41e-3	0.06	110.89	6.03
Domains + Hemispheres + groups + Domains ✻ groups + Hemispheres ✻ groups	0.05	1.37e-3	0.02	276.78	5.30
Domains + Hemispheres + groups + Domains ✻ Hemispheres	0.05	1.08e-3	0.02	348.91	1.86
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups	0.05	4.22e-4	7.60e-3	895.57	3.16
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Hemispheres ✻ groups	0.05	2.37e-4	4.27e-3	1593.09	6.74
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups + Hemispheres ✻ groups	0.05	8.54e-5	1.54e-3	4427.16	2.93
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups + Hemispheres ✻ groups + Domains ✻ Hemispheres ✻ groups	0.05	2.16e-5	3.89e-4	17501.44	3.06

Note. All models include subject, and random slopes for all repeated measures factors.

Table 9
Descriptive Data for Bayesian Repeated Measures ANOVA conducted on between-conditions classifications function of Domain (Phonological, Semantic, Visual), Group (Young, Elderly), and Hemispheres (Left, Right) in the Pars Orbitalis
Descriptives

						95% Credible Interval	
Domains	**Hemispheres**	**groups**	**Mean**	**SD**	**N**	**Lower**	**Upper**
Visual	Right	1	0.56	0.09	34	0.53	0.59
		2	0.59	0.08	29	0.56	0.62
	Left	1	0.57	0.09	34	0.54	0.60
		2	0.57	0.09	29	0.54	0.61
Phonological	Right	1	0.55	0.08	34	0.53	0.58
		2	0.55	0.08	29	0.52	0.58
	Left	1	0.55	0.08	34	0.52	0.58
		2	0.55	0.08	29	0.52	0.57
Semantic	Right	1	0.57	0.08	34	0.54	0.60
		2	0.53	0.10	29	0.50	0.57
	Left	1	0.59	0.07	34	0.56	0.61
		2	0.56	0.10	29	0.52	0.60

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Table 10

Model comparison for Bayesian Repeated Measures ANOVA conducted on between-conditions classifications function of Domain (Phonological, Semantic, Visual), Group (Young, Elderly), and Hemispheres (Left, Right) in the Pars Orbitalis.

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{01}	error %
Null model (incl. subject and random slopes)	0.05	0.52	19.29	1.00	
Domains	0.05	0.16	3.53	3.16	1.04
groups	0.05	0.12	2.42	4.37	3.71
Hemispheres	0.05	0.08	1.51	6.68	1.74
Domains + groups	0.05	0.04	0.67	14.33	1.38
Domains + Hemispheres	0.05	0.02	0.44	21.66	1.35
Domains + groups + Domains ✻ groups	0.05	0.02	0.35	27.22	1.91
Hemispheres + groups	0.05	0.02	0.33	28.99	3.01
Domains + Hemispheres + Domains ✻ Hemispheres	0.05	8.96e-3	0.16	57.76	3.25
Domains + Hemispheres + groups	0.05	5.71e-3	0.10	90.58	3.79
Hemispheres + groups + Hemispheres ✻ groups	0.05	3.52e-3	0.06	146.81	6.46
Domains + Hemispheres + groups + Domains ✻ groups	0.05	2.84e-3	0.05	182.24	3.10
Domains + Hemispheres + groups + Domains ✻ Hemispheres	0.05	1.86e-3	0.03	278.29	2.85
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups	0.05	1.09e-3	0.02	474.96	8.73
Domains + Hemispheres + groups + Hemispheres ✻ groups	0.05	1.06e-3	0.02	486.27	3.36
Domains + Hemispheres + groups + Domains ✻ groups + Hemispheres ✻ groups	0.05	5.41e-4	9.73e-3	957.06	3.08
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Hemispheres ✻ groups	0.05	3.76e-4	6.76e-3	1377.38	3.93
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups + Hemispheres ✻ groups	0.05	1.87e-4	3.36e-3	2770.17	3.85

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{01}	error %
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups + Hemispheres ✻ groups + Domains ✻ Hemispheres ✻ groups	0.05	4.37e-5	7.86e-4	11842.89	10.14

Note. All models include subject, and random slopes for all repeated measures factors.

Table 11

Descriptive Data for Bayesian Repeated Measures ANOVA conducted on between-conditions classifications function of Domain (Phonological, Semantic, Visual), Group (Young, Elderly), and Hemispheres (Left, Right) in the Pars Opercularis

Domains	Hemispheres	groups	Mean	SD	N	95% Credible Interval Lower	95% Credible Interval Upper
Visual	Right	1	0.59	0.11	34	0.55	0.63
		2	0.61	0.11	29	0.57	0.65
	Left	1	0.58	0.09	34	0.55	0.61
		2	0.60	0.09	29	0.57	0.64
Phonological	Right	1	0.59	0.10	34	0.56	0.62
		2	0.55	0.08	29	0.52	0.58
	Left	1	0.55	0.08	34	0.52	0.58
		2	0.56	0.08	29	0.53	0.59
Semantic	Right	1	0.57	0.09	34	0.54	0.60
		2	0.59	0.10	29	0.55	0.63
	Left	1	0.57	0.09	34	0.54	0.60
		2	0.57	0.11	29	0.53	0.61

Table 12

Model comparison for Bayesian Repeated Measures ANOVA conducted on between-conditions classifications function of Domain (Phonological, Semantic, Visual), Group (Young, Elderly), and Hemispheres (Left, Right) in the Pars Opercularis

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{01}	error %
Null model (incl. subject and random slopes)	0.05	0.36	10.26	1.00	
Domains	0.05	0.21	4.86	1.71	1.22
Hemispheres	0.05	0.13	2.65	2.83	2.40
groups	0.05	0.09	1.69	4.23	1.21
Domains + Hemispheres	0.05	0.07	1.44	4.89	2.42
Domains + groups	0.05	0.05	0.98	7.00	1.79
Hemispheres + groups	0.05	0.03	0.56	12.03	1.70
Domains + Hemispheres + groups	0.05	0.02	0.33	20.45	1.83
Domains + groups + Domains ✻ groups	0.05	0.01	0.23	28.75	2.28
Hemispheres + groups + Hemispheres ✻ groups	0.05	6.50e-3	0.12	55.90	2.51
Domains + Hemispheres + Domains ✻ Hemispheres	0.05	5.47e-3	0.10	66.42	5.98
Domains + Hemispheres + groups + Domains ✻ groups	0.05	4.68e-3	0.08	77.55	3.73
Domains + Hemispheres + groups + Hemispheres ✻ groups	0.05	3.99e-3	0.07	91.03	4.34
Domains + Hemispheres + groups + Domains ✻ Hemispheres	0.05	1.37e-3	0.02	264.35	5.96
Domains + Hemispheres + groups + Domains ✻ groups + Hemispheres ✻ groups	0.05	9.44e-4	0.02	384.54	2.80
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups	0.05	3.20e-4	5.76e-3	1134.38	2.72
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Hemispheres ✻ groups	0.05	3.13e-4	5.63e-3	1160.76	6.83
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups + Hemispheres ✻ groups	0.05	6.74e-5	1.21e-3	5386.12	3.12

Model Comparison

Models	P(M)	P(M|data)	BF_M	BF_{01}	error %
Domains + Hemispheres + groups + Domains ✻ Hemispheres + Domains ✻ groups + Hemispheres ✻ groups + Domains ✻ Hemispheres ✻ groups	0.05	4.30e-5	7.73e-4	8450.83	3.43

Note. All models include subject, and random slopes for all repeated measures factors.

Discussion

This PhD thesis examined the domain-general vs. domain-specific nature of RI by investigating the cognitive and neural aspects of RI across phonological, semantic, and visual domains in both young and elderly adults. We will start this General Discussion by summarizing the main results. We will then discuss the theoretical implications of our results and their potential limitations. We will close this section by discussing future perspectives for research on the domain-specificity of RI.

Overview of the Results

Study 1 was a focused mini-review. By considering behavioral, neuropsychological, and neuroimaging studies, the review examined the evidence for and against a domain-general nature of RI processes by focusing on visual, verbal phonological, and verbal semantic domains. Behavioral studies indicated overall low associations between RI capacity across domains. Still, we also highlighted the lack of studies directly comparing RI capacity across domains with well-matched and comparable task designs. Neuropsychological studies revealed dissociations in RI abilities between the three domains, but systematic comparisons were lacking. Results of neuroimaging studies on RI were compatible with the left vs. right hemisphere implication of the IFG in verbal vs. visual RI, with further possible dissociations within the left IFG for phonological vs. semantic RI. But, once more, we concluded that these results must be considered cautiously, given the disparity of tasks and paradigms used to compare RI between domains.

Study 2 was a preparatory, normative study determining imageability, concreteness, and emotional valence values for the stimuli to be used in subsequent experiments on RI. The database included 177 nouns and 165 verbs. The data collection process involved 258 native French speakers from France and Belgium. Mean values for imageability, concreteness, and emotional valence ratings were calculated for each stimulus; inter-rater reliability was also determined for each dimension.

Study 3 examined the question of domain-specific vs. domain-general RI abilities by comparing RI abilities in young and elderly adults across three domains (phonological, semantic, visual) and two tasks. Critically, the different domain conditions were carefully matched, and the task structure was identical, with the only change being the stimuli. Furthermore, we compared RI in young and elderly participants to determine the domain-specificity of RI decline across the aging process. The first task involved a similarity-judgment task with variable interference buildup, commonly used to assess RI in the verbal domain. The task required participants to judge the closest match between two test-items based on pre-activated semantic, phonological, or visual information. Pre-activated information either facilitated the selection of the correct test item or caused interference that needed to be resisted (RI condition). The second task focused on RI within a working memory context, examining the extent to which results from a direct stimulus-matching task can be extended to a task involving stimuli held in memory. This task was a recent-negative paradigm, where participants memorized a sequence of stimuli followed by a probe item that was either neutral or similar to items from current or previous memory lists. Similar items were considered to generate interference with memoranda and needed to get rejected for a correct response decision. We observed a general age-related decline of RI abilities for both tasks that did not reliably interact with the domain. On the other hand, correlational analysis overwhelmingly supported evidence for an absence of both within-domain and between-domain associations of RI abilities. Overall, the results support the view that RI processes are highly specific.

Study 4 examined the univariate and multivariate neural substrates associated with RI across phonological, semantic, and visual domains in young and elderly participants. In an fMRI experiment, young and elderly participants performed a similarity-judgment task close to the one used in Study 3 involving phonological, semantic, or visual interference build-up. For both age groups, domain-specific RI effects were observed at the univariate level, with increased involvement in the phonological domain of the right angular gyrus and the right lingual gyrus, in the semantic domain of the bilateral inferior frontal gyrus (IFG), the bilateral superior parietal and angular gyri and the left middle temporal gyrus, and in the visual domain of the middle/superior frontal gyri and occipital gyri. At the multivariate level, although RI effects could be decoded from neural patterns in the bilateral IFG for all domains and age groups, between-domain prediction of RI conditions was associated with Bayesian evidence for the null hypothesis. Overall, these results indicate domain-specific.

Implications for the Domain-general vs. Domain-specific Debate Nature of RI

This section will discuss our results by examining the novel evidence they bring for a domain-general view vs. a domain-specific nature of RI by focusing on Study 3 and Study 4 of our thesis.

Evidence for a Domain-general View

On the one hand, one could argue that several aspects of our results may support a domain-general view of RI. First, in Study 3, a general age effect was observed that did not reliably interact with the RI domain. Only in Study 4 was a triple interaction observed for behavioral results (for response times only). This triple interaction, however, was driven more by the younger group showing a more pronounced RI effect in the phonological domain vs. the other domains, than by the older group, who showed globally increased RI effects. Also, age did not interact with the univariate or multivariate neural substrates associated with the different RI conditions at the neuroimaging level, revealing a general age effect at the neural level. Second, the neuroimaging results indicate a joint involvement of anterior, mid, and posterior IFG areas in RI for all conditions at the multivariate level. Together, this set of results could be compatible with a domain-general view of RI.

Evidence for a Domain-specific View

On the other hand, numerous other results could be more in line with a domain-specific perspective on RI. First, in Study 3, when comparing all tasks, a domain-by-group interaction was observed for the response-time-based interference score indicating more substantial age-related RI effects in the semantic domain relative to the two other domains.

The correlation analysis overwhelmingly supported the absence of correlations between RI effects across domains. Even within-domain (between-task) correlations lacked robust support, with only a few task-specific correlations associated with evidence for their presence. These results, revealing dissociations rather than associations, were obtained while carefully matching the task variants' structure for probing RI across the phonological, semantic, and visual domains, contrary to previous studies. Furthermore, using a Bayesian statistical framework provides positive evidence for the *absence* of associations. It makes it possible to interpret correlations that would merely be labeled as 'non-significant' within a frequentist statistical approach.

These results are also supported by Study 4. At the behavioral level, a more pronounced RI effect was observed in the phonological domain relative to the semantic and visual domains indicating some possible domain-specific differences in RI. Univariate analyses further support this view, revealing domain-specific involvement of distinct brain regions, such as the right angular gyrus and right lingual gyrus for phonological RI, the bilateral IFG, bilateral superior parietal and angular gyri, and the left middle temporal gyrus for semantic RI, and the middle/superior frontal gyri and occipital gyri for the visual RI. Most critically, although multivariate analyses demonstrate the ability to decode RI effects from neural patterns in the bilateral IFG across domains and age groups, the between-domain prediction of multivariate neural patterns associated with RI was associated with clear Bayesian evidence for the null. The latter result indicates that the same IFG regions involve distinct neural processes depending on the domain RI needs to operate.

Domain-general vs. Domain-specific Perspectives on RI: Who Wins?

The domain-specific view of RI seems to be supported most strongly, if not overwhelmingly, by our results. These results also mirror the main conclusion of the focused mini-review (Study 1), in which we considered that the bulk of evidence supported the domain-specific view of RI. This assertion was, however, made very cautiously in Study 1, given that existing studies did not use well-matched tasks when comparing RI across domains or already compared a minimal number of domains. Studies 3 and 4 responded to that concern by using maximally matched task variants for eliciting RI across three domains. And yet, most results were associated with domain-specific RI effects at both behavioral and neural levels. At the same time, it is crucial to recognize the presence of some common aspects for RI across domains as age-effects on RI did not reliably interact with the RI domain (despite some sporadic interactions), indicating at the least that RI processes, even if domain-specific, are affected by age in the same manner across domains. Also, the common involvement of the bilateral IFG (despite hosting domain-specific RI processes) indicates a more general role of these areas in RI that will be further discussed in the following sections.

Resistance-to-Interference and its Models

In the Introductory part (see Chapter 1), we briefly discussed different theoretical frameworks of RI processes. In this section, we will discuss to what extent our results are compatible or not with these frameworks. As a reminder, Dempster (1993) identified three processes: resistance to perceptual, motor, and linguistic interference. Harnischfeger (1995) distinguished behavioral and cognitive RI, intentional and unintentional RI, and emphasized the difference between inhibition and RI. Nigg (2000) proposed executive, motivational, and automatic RI categories, including control of interference, cognitive suppression, behavioral suppression, and oculomotor control. Friedman and Miyake (2004) highlighted RI to prepotent responses, distracter interference, and proactive interference. Hasher and colleagues (Hasher et al., 2008; Hasher & Zacks, 1988) classified RI based on restraining, deleting, and accessing functions.

Theoretical Models

Our results provide strong, if not overwhelming, support for the domain-specific view of RI, dissociating verbal and verbal RI. Our findings reveal evidence in favor of differences in RI across various cognitive domains, mirroring the distinct processes proposed by Dempster's framework. Indeed, Dempster proposed a framework that dissociates motor, linguistic, and perceptual RI. Therefore, Dempster's model proposes that RI mechanisms can operate independently in each domain. This means that individuals may exhibit strong RI abilities in one domain while showing weaker RI in another domain. The alignment of our results with Dempster's model provides compelling support for the notion of domain-specific RI. The observed variations in RI performance linguistic and perceptual domains indicate that individuals may possess unique inhibitory abilities tailored to specific cognitive tasks.

For completeness, Dempster also proposed that RI could vary across a temporal dimension, often referred to as proactive, coactive, retroactive, and concurrent RI. Using a similar design for each domain, we controlled for that aspect, the temporal order of the stimuli being the same for each domain in each task. This also allowed us to control for a last aspect of Dempster's proposal: the external or/and internal origin of RI (i.e., distractor task activity or associations occurring during a delay interval). Still, one may underline that we cannot account for a participant eliciting their representations when facing a stimulus; therefore, we only assume that we controlled for the distracting characteristics of our tasks and for the duration of the delay interval, which was relatively short (i.e., 1.5 sec) to avoid mind-wandering.

Regarding the remaining classifications of Friedman and Miyake, Harnischfeger, and Nigg, we only relate to their use of cognitive RI, i.e., '*for mental processes'* and '*suppressing irrelevant stimuli to protect working memory and/or attention,'* respectively. Further assumptions related to their models cannot be provided from our studies as we did not examine RI concerning broader aspects such as the motivational one - for example.

Finally, our results also align well with the A-O-STM model from Majerus presented in the first chapter of the Introduction. In this model, executive and attentional processing play a central role, interacting with the language system for encoding and maintaining item information on the one hand and with a system for processing serial order on the other (Majerus, 2014, 2018b). The present thesis and its results confirm the existence of a domain-specific executive component (i.e., RI).

Computational Models of RI

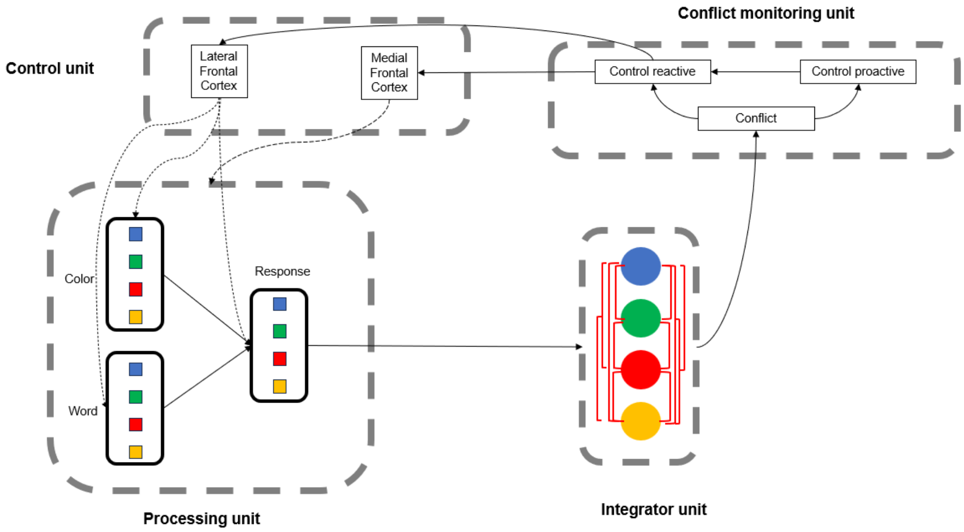
Interestingly, our findings seem to align with recent computational approaches that assume that cognitive control processes, particularly those involved in RI, are tailored to specific tasks (O'Reilly et al., 2010; Verbeke & Verguts, 2021; Wiecki & Frank, 2012). Verbeke and Verguts (2021) recently proposed a computational model emphasizing the synchronization of neural oscillations between prefrontal control systems and task-specific representational domains. This synchronization process is adapted dynamically, as a function of the task's nature and domain, by synchronizing neural oscillations in the prefrontal control systems with those in the relevant representational substrates required for a specific task. Additionally, these adaptations can be further optimized through procedural learning processes (Verguts & Notebaert, 2009). The procedural learning system is responsible for acquiring and fine-tuning task-specific representations.

In contrast, the cognitive control system allocates cognitive resources and suppresses inappropriate responses. This model also implies that task-specific representations become more efficient and automatic over time through procedural learning. This allows the cognitive control system to focus its resources on other, more demanding aspects of the task if necessary. The model also highlights the role of conflict monitoring and adaptation mechanisms in cognitive control, which helps detect and resolve conflicts between competing task demands. Furthermore, this model distinguishes the concept of "primary" and "secondary" controllers (Verbeke & Verguts, 2021; Verguts, 2017a, 2017b). Primary controllers operate within specific visual perception, language, or motor control domains. In contrast, secondary (central) controllers function to moderate, inhibit, and synchronize primary controllers, see Figure 3 (see also Holroyd & Coles (2002) and O'Reilly et al. (2010) for similar frameworks assuming hierarchical control processes).

In the present thesis, we observed that the multivariate signals in the IFG differentiate between RI and non-RI conditions in all three domains in both younger and elderly adults. However, these distinctions are observed in a domain-specific manner (i.e., no between-domain prediction). This result aligns well with the mentioned models suggesting task-specific neural adaptations between the prefrontal cortex (i.e., the secondary controller) and modality-specific areas in the posterior regions of the brain (i.e., the primary controllers) (Verbeke & Verguts, 2021; Verguts, 2017b). The general multivariate decoding of RI conditions in the IFG is, on the other hand, consistent with its role as a central (secondary) controller. Overall, these results also align with the theoretical model of statistical learning proposed by Frost et al. (2015). They proposed that contributions of domain-general learning principles are tailored to operate within specific modalities. The authors also suggested that the potential contributions from brain regions are partially shared, indicating commonalities in learning across different modalities (Conway & Christiansen, 2005).

Figure 3

Simplified Version from the Model Architecture proposed by Verbeke & Verguts, 2021, p.2396.



Overall, our findings and the computational approaches and models discussed highlight the importance of tailoring cognitive control, particularly RI, to specific tasks. By recognizing the coexistence of domain-specific and domain-general processes and understanding the dynamic synchronization between prefrontal control systems and task-specific domains, we can better understand and model the intricate mechanisms of RI (and cognitive control) in various contexts. To sum up, RI will have a diverse range of neural and cognitive configurations corresponding to the various tasks and domains, underscoring the significance of task-specific procedures and rules. These procedures and rules can be acquired through experience and training (Huycke et al., 2022).

The Effect of Age on RI

The studies conducted in the context of this PhD thesis have also investigated the interaction between domain effects on RI and age. More specifically, Studies 3 and 4 examined whether RI abilities were affected by age in a domain-general or a domain-specific manner.

Study 3 revealed age effects for both response times and accuracy but without presenting a reliable interaction with the domain, except for the response time interference score when analyzing both tasks together. This interaction indicated more strongly slowed responses in the elderly group for semantic RI than in the young group and the other domains. Study 4 revealed no age effects for accuracy on the similarity judgment task, while the task was the same as the one used in Study 3. An age effect was, however, also observed for response times, which furthermore interacted with the domain, indicating pronounced interference effects in all three domains for the elderly group. The younger group showed a much stronger interference effect in the phonological domain compared to the two other domains. Both studies are thus consistent with age effects on RI response times but not necessarily on accuracy. Interactions of the age effect with the domain effect appear complex and inconsistent across the two studies.

On the one hand, it could be argued that Study 4 had less statistical power to reveal age effects, given that number of participants was reduced relative to the sample size in Study 3. Thus, Study 4 may only have had a sufficient sample size to evidence age effects for measures associated with large age effects, such as reaction times, but not accuracy. Indeed, other variables that could have explained these between-study differences seemed quite similar between the two studies, such as educational level, age, or vocabulary level (see Table 1). The more pronounced age effects on response times align with age-related changes in processing speed and associated theoretical frameworks considering that processing speed is one of the first cognitive domains to show an age-related decline (Salthouse, 1996).

Table 1

Summary of the Participants 'characteristics from Studies 3 and 4.

	Study 3		Study 4	
	Young	Elderly	Young	Elderly
Level of education	13.91	13.32	15.44	14.97
Vocabulary level	21.80	25.15	24.47	29.31
Age	23.32	67.49	25.09	67.55

Our results are also in line with the Interference Theory / Inhibitory Deficit Theory (see Introduction, Chapter 3), which states that one of the primary contributors to age-related disruptions in higher-order cognitive processes is a decline in the efficiency of inhibitory mechanisms that enable individuals to minimize the impact of irrelevant information during tasks, and this mainly at the level of response times (Hasher & Zacks, 1988). Schumann et al. (2023) indeed recently showed that the primary factor leading to longer response times in elderly adults is processing interference occurring before the decision. On the other hand, regarding response accuracy, our results are somewhat less consistent with the literature and our studies, except when considering that reduced statistical sensitivity due to reduced sample size could explain these differences. However, note that other studies involving similar sample sizes as ours obtained group effects for RI accuracy scores (e.g., Martin et al., 2006; Moroni & Bayard, 2009; Palladino & De Beni, 1999). Still, this last statement also fuels the argument that aging is heterogenous and joins the studies showing that age and decline are not mandatorily concomitant.

Therefore, it is important to note that aging is a heterogeneous process. Although the executive-frontal hypothesis of aging (see Introduction) takes root in robust studies, this theory faces some controversies. Greenwood (2000) reviewed the literature on working memory, visuospatial attention, face recognition, and implicit memory as a set of cognitive functions that engage the prefrontal, parietal, temporal, and occipitotemporal cortices variably. She concluded that there was weak and conflicting evidence that cognitive functions more strongly associated with frontal involvement were selectively and differentially affected by aging. Furthermore, in a more recent paper, Kouwenhoven and Machado (2023) investigated eight RI and verbal and visuospatial WM measures in young and elderly adults. Their results indicated that a deficit in RI measures depends on the tasks' WM requirements. In the context of the present PhD thesis, it could be argued that the similarity judgment task had a relatively low WM load, potentially explaining the inconsistent age effects regarding accuracy. At the same time, this possible explanation is contradicted by our own results, Study 3 indicating stronger age effects on interference scores in the similarity judgment task than in the recent negative tasks. Therefore, a deeper understanding of RI and cognitive control development requires considering cellular, circuit, and systems-level interactions in the brain.

In this context, Luna et al. (2015) reviewed cellular, circuit, and systems-level cognitive control models, proposing an integrative approach. The authors suggested that strengthening dynamic interactions between neural systems supporting cognitive control, such as WM, inhibitory control, and performance monitoring, underlies its maturation. Shortly, the model suggests that these components involve distinct and overlapping brain regions, with some regions specialized for specific cognitive control processes and others playing an integrative role. It is worth noting that the authors encompassed inhibitory control, performance monitoring, and working memory into the broader term ‘cognitive control.’ Their review also aligns with their previous studies specifying that different brain regions within each circuit exhibited unique developmental paths, suggesting that a hierarchical pattern of brain activation underlies the gradual development of adult-like inhibitory control (Ordaz et al., 2013).

However, very few models had embedded the aging varia into its parameters. In 2016, Mooney et al. (2016) suggested an integrated overview of aging as a basis to embed the different existing computational models (e.g., Li et al., 2001; Nieuwenhuis et al., 2002) – see Figure 1, p.124, in their article. Mooney and her colleagues discussed the need for modelizing aging with the help of computational systems biology. To date, no model has been able to encompass age-related mechanisms (see Figure 3 in the Introduction) into a single model. Considering the impact of life-course experiences, such as physical activity, nutrition, and exposure to stressors, on cognitive and brain reserve, it is plausible that individuals' cognitive abilities may differ based on these factors (see Discussion from Article 4; Cabeza et al., 2018; Nyberg et al., 2012). The degree of neural synchronization and de-integration in the brain might be influenced by one's life experiences, potentially contributing to variations in cognitive decline observed among elderly populations.

In conclusion, the interplay between cognitive aging, life-course experiences, and neural mechanisms is intricate and calls for a holistic approach to understanding healthy cognitive aging. By acknowledging the complexities of aging, considering integrative RI (and cognitive control) models, and accounting for the influence of life experiences, researchers can make significant strides toward enhancing our comprehension of cognitive aging and designing effective interventions to support brain health throughout the lifespan. Future research in the domain of computational systems biology may provide new opportunities to develop comprehensive models that encompass age-related mechanisms and shed light on the multifaceted processes of cognitive aging.

Limitations

How to properly assess RI across different domains?

The first question we must address is whether our tasks allowed us to generate the same level of RI across the three domains we investigated. As stated in Study 1, evaluating the same cognitive process across different domains can be challenging. As mentioned several times, a significant focus of this thesis was to provide tasks that are matched as closely as possible for their different domain variants. Yet, we may not have accomplished our goal completely.

In particular, Study 3 indicated that the phonological variants of our task may have been less prone to interference effects, particularly for the similarity judgment task and the accuracy measure. This issue was already raised in an early study by Attout, Grégoire, et al. (2022), considering that this task's facilitation and interfering conditions may not be optimally contrasted. The task we used was already an optimized version of the task used by Attout, Grégoire, et al. (2022). For example, in their Facilitation condition, the priming nonword shared both vowels with the two target nonwords and one vowel and its position with the correct test nonword, facilitating its selection. Meanwhile, only the non-informative vowel was activated beforehand in the interfering conditions through a prime nonword. This prime nonword shared the non-informative vowel and its position with the target nonwords and both vowels of the incorrect test nonword. The task for participants was to inhibit the incorrect test nonword and select the correct test nonword that shared a vowel and its position with both target nonwords. Therefore, both conditions were less discriminable. In our studies, we created more contrasted conditions. In the interfering condition, the prime nonword, via its phonological similarity, pre-activated the wrong test nonwords. For example, for the target nonwords "vuta" and "muka" and the test nonwords “maku” and “bova,” the correct test nonword is “bova.” Still, the prime “muké” will pre-activate “muka,” which then needs to be inhibited to allow the correct test nonword to be chosen. In the facilitation condition, the prime nonword directly pre-activates the correct test nonword by sharing both vowels at the same places, the item to reject being completely different.

Furthermore, like Attout, Grégoire, et al., we used nonwords to maximize phonological processing requirements, while previous studies focusing on phonological RI often used lexico-semantic material such as words (Gold et al., 2005; Hamilton & Martin, 2007a; R. C. Martin & Lesch, 1996; Thompson-Schill et al., 2002). In other words, we believe the phonological variants of the tasks we used focused maximally on RI at the phonological level relative to previous studies. Still, we cannot directly demonstrate that the inherent potential for interference was precisely matched between the different task versions.

The same reasoning could be made regarding the visual variant of the tasks. We used meaningless visual stimuli to avoid the impact of associated semantic variables and processing levels (Hamilton & Martin, 2005, 2007b). Nonetheless, we agree that this may have made the interfering or facilitatory cues in the visual task less intense regarding representational activation and may have increased visual feature identification and discrimination demands. Moreover, we cannot rule out the possibility that participants may have attributed personal meanings to the 'meaningless' visual stimuli presented in the tasks.

Note also that there were general domain differences in both paradigms used in this study. On one side, phonological and semantic items were displayed auditorily, whereas visual items were displayed in the middle of the screen. At the same time, a cross was displayed in the center of the screen to maintain participants' visual focus on the screen so that they knew to answer without eliciting further visual-related processing as the condition required. Taken together, it could be argued that these dissimilarities might inflate the chances of detecting differences between tasks because of the maximal contrasts between domains and tasks. The same consideration applies to the probe presented in the similarity-judgment task in the verbal domains vs. the visual domain. Yet, we choose to maximize contrast between domains and subsequent cognitive processes and, therefore, to identify any association or similarity as being attributed to the possible distinct RI processes.

In relation to the material used, a second question we need to address is whether the age-related sensory processing difficulties may have interacted with the task and domains, and this is mainly for the processing of phonological information due to age-related hearing loss (Burke & Osborne, 2007). The deterioration of visual and auditory sensory processes during aging complicates the identification of cognitive processes underlying cognitive changes. It should, however, be noted here that in both Study 3 and 4, we had administered a short list of words semantically or phonologically related before the experiment. This was made to ensure that participants could discriminate words adequately with an adequate auditory volume. In addition, volume was set up at 50% of the computer capacity and adapted by adding/removing 10 volume points if the participants could not distinguish and repeat the test-items. Each task, including auditory items, was displayed with headphones with the appropriate volume. The mean volume across all participants was around 50%. It is also noteworthy that high-performance levels were observed in-scanner in Study 4, indicating that older adults had no particular difficulty processing stimuli, even in a noisier environment.

Another question to be addressed is the number of tasks required to evaluate RI across domains. In this PhD thesis, two tasks were administered in Study 3 and only one in Study 4. Some previous studies assessed RI (or inhibitory-related processes) using a much larger set of tasks but without necessarily contrasting different RI domains. For instance, Rey-Mermet et al. (2018) used eleven tasks such as the antisaccade, stop-signal, color Stroop, number Stroop, arrow flanker, letter flanker, Simon, global-local, positive and negative compatibility tasks, as well as the n-2 repetition cost in task switching. Such a comprehensive set of measures allowed them to conduct Structural Equation Modelling analyses to identify latent RI variables and their relationships. However, this comes at the cost of using tasks not necessarily matched in response mode, task difficulty, sensory requirements, etc., and is not ideal when investigating domain-specific effects. Overall, using a more extensive set of tasks assessing the different domains under investigation would be an ideal goal to reach as it would allow for more advanced analysis strategies. Still, it remains crucial that the different tasks are well-matched across domains. As mentioned, using two or more different highly controlled tasks for each domain cannot be easy to achieve.

Directly related to this question are the domains to be compared. Indeed, we addressed phonological, semantic, and visual domains, which is already an improvement relative to earlier studies, which rarely compared more than two domains when directly making domain comparisons. However, what about including other domains, such as motor, kinesthetic, or spatial domains? Spatial RI involves manipulating and organizing visual-spatial information, requiring individuals to resist interference from competing spatial cues or distracting stimuli. Based on Kowialiewski et al. (2022), the potential for spatial interference can be manipulated by varying the spatial proximity between items presented at consecutive serial positions in a WM task. The authors showed that the presence of spatially closed items impacted recall performance. This kind of manipulation could be adapted to address spatial RI directly. Motor RI involves resisting automatic or prepotent motor responses (A. R. Aron et al., 2016). This domain implies situations where individuals must suppress habitual or irrelevant motor actions. Two tasks are well-known for assessing motor RI: the Go/No-Go and the Stop-Signal (see Introduction and Study 1 for description). Kinesthetic RI refers to resisting interference or distractions related to bodily movements and proprioceptive sensations. It involves inhibiting irrelevant or conflicting kinesthetic information during motor tasks.

For example, Hecht and Reiner (2010) extended the Stroop task to kinesthetic and haptic domains. One of their experiments assessed hand movements in different directions. The participants were presented with a circle at the center of their visual field. They held a stylus with their hand, corresponding to a visual representation (a stick with a small ball at its tip) positioned in the middle of the circle. During each trial, the computer applied a consistent force (0.6 Newton) using the stylus's engine, pushing the participants' hands slightly in one of three directions: rightward, leftward, or upward. As a result, while holding the stylus, the participants' hand was gently displaced outside the circle in one of these three directions. The authors showed an effect for a kinesthetic Stroop effect. Assessing RI in kinesthetic and motor domains appears particularly challenging, compared to visual and verbal domains, as both often require intervention from external objects (e.g., a computer applying weight, an experimenter initiating a movement, etc.).

Finally, research in aging comes with some limitations. One of them we can pinpoint in this thesis is that all older participants were grouped, despite spanning a wide age range of 60 to 80 years. This design, as noted, fails to account for the continued age-related decline observed among older adults (also mentioned in Kouwenhoven & Machado, 2023). Previous research that categorized older participants into "young-old" (60-74 years) and "old-old" (75 years and older) groups found that the old-old participants performed significantly worse on various neuropsychological tasks compared to their younger counterparts (Christensen et al., 1994; Palladino & De Beni, 1999; Persad et al., 2002). Future research to investigate age-related differences in working memory and RI-related functioning should consider employing a study design that compares young, young-old, and old-old adults or go for a longitudinal study.

RI: a conceptual challenge

We mentioned in the Introductory Part that historically, ‘inhibition’ and ‘interference’ were often used as synonyms. For example, consider the definition of RI proposed by the Dictionary of Psychology of the American Psychology Association: “*the **blocking** of learning or of memory retrieval by the learning or remembering of other conflicting material. Interference has many sources, including prior learning, subsequent learning, competition during recall, and presentation of other material.”*, based on the work of Anderson (2003) and Anderson and Levy (2010). In this definition, a parallel is made between interference as a blocking mechanism, which can arise from proactive interference (i.e., interference in new learning due to previous learning of similar or related material), retroactive interference (i.e., when the acquisition of new knowledge or exposure to fresh information hampers the capacity to recall previously learned material or execute previously acquired activities), output interference (i.e., a disturbance in the recollection of previously learned information where the act or process of recalling one item hinders the ability to remember other items.), or interpolated tasks (i.e., task introduced between two experimental tasks, either to occupy time or to conceal the link between the two crucial tasks).

According to Dempster and Brainerd (1995), interference refers to processes that cause performance decrements in a task (i.e., a pattern of results or the mechanisms responsible for that pattern, such as occlusion or blocking). In contrast, inhibition would refer directly to the observed decrements. This implies that whenever there is inhibition, there is necessarily interference. By extension, if various types of interference exist, the association between interference and inhibition is likely to be contingent upon the specific nature of the interference. On the other hand, other authors have proposed that inhibition and interference should be more clearly separated (Costa & Friedrich, 2012; Wante et al., 2018).

For example, supporters of interference theory often attribute forgetting to occlusion or blocking, as in the APA definition. When a retrieval cue is linked to two memories, the stronger memory becomes more easily accessible, thereby obstructing the retrieval of the weaker one: inhibition is a consequence of differences in memory strength and associated interference. On the other hand, proponents of the inhibition theory propose that forgetting results from a more active process (Anderson, 2003; Anderson & Hulbert, 2021). To retrieve Memory B using

Cue A, an active suppression (i.e., inhibition) of the association between Cue A and Memory C is needed.

At the same time, the term 'inhibition' itself suffers from ambiguity. MacLeod (2007) highlighted that 'inhibition' has two distinct meanings in cognitive psychology: empirical and theoretical. The empirical meaning refers to a pattern of results and is equivalent to retrieval failure in a memory task. For example, if participants study a list of words that includes both once- and twice-presented words, their performance will be better for those presented twice. In this case, one could say that the repeated words inhibited the once-presented words, using the empirical definition of inhibition. The empirical meaning of inhibition is straightforward and describes the observed phenomenon of better performance for repeated items compared to non-repeated items. However, the theoretical meaning of inhibition suggests active mechanisms by which unwanted information is suppressed or blocked in memory, requiring directed effort.

Another confusion is associated with "inhibitory control" (Tiego et al., 2018). Some defined inhibitory control as suppressing goal-irrelevant stimuli, representations, and behaviors (Anderson & Weaver, 2009). At the same time, some authors defined it as multifaceted involving different types of inhibition processes, such as *interference control* and *response inhibition,* depending on the activity that needs to be inhibited (Salvia et al., 2021). Its use can confuse the interference and inhibition terminology due to the ambiguity and overlapping use of the different terms in different contexts. While inhibitory control, inhibition, and interference may be distinct concepts, they are not entirely independent. Inhibitory control often involves inhibiting interference from irrelevant or conflicting information. Boundaries between these concepts might become blurred in certain contexts, making it challenging to differentiate them in experimental settings.

In summary, the confusion surrounding interference, inhibition, and inhibitory control calls for a consensus-based conceptual clarification. Studies declaring to investigate 'interference' by some authors could be considered to investigate 'inhibition' by other authors, or vice-versa. Regarding the present thesis, the latter authors may consider that we examined the domain-specificity of inhibition or inhibitory control rather than resistance-to-interference.

Future perspectives

Refining behavioral measures of RI via eye-tracking measures

The present studies explored the domain-general vs. domain-specific nature of RI, but other aspects remain to be investigated, such as the visual strategies underpinning RI in tasks involving visual stimuli. Eye-tracking measures may be beneficial in this context as they allow us to examine how participants handle interference and, more precisely, how they allocate their attention and fail to resist unnecessary information when processing this information. Participants who have an excellent ability to resist interference should selectively attend to relevant stimuli and ignore distracting or irrelevant information (Ayasse & Wingfield, 2020; Harkin et al., 2012; Huber et al., 2014; Hutton, 2008; Liu et al., 2004; Mainville et al., 2015; Noiret et al., 2017; Sahan et al., 2021; Schik et al., 2000). Two main eye-tracking measures are based on the frequency and duration of fixations on distractors (Zhang et al., 2006). If participants successfully resist interference, they should be less likely to fixate on distractors or spend less time looking at them. In contrast, if participants are less successful in RI, they may be more likely to track distractors or spend more time looking at them (Evdokimidis et al., 2002; Tatler & Hutton, 2007).

In the present context, investigating the visual strategies could be fruitful for future experiments using the tasks we developed. In Study 3 and Study 4, we used a similarity-judgment task in which target and test items were presented visually. We could determine the fixation duration of distractor test items or which of the correct and distractor items is fixated first. Indeed, participants providing a correct answer may still differ in their visual strategies. Some of these participants spend little time on the distractor stimulus. In contrast, others may spend more time on it, indicating stronger interference even if eventually choosing the correct test item. This would allow for a more sensitive measure than dichotomous accuracy measures and may also allow to reveal more subtle age effects. These measures based on the proportion of total fixation time per zone of interest could be complemented by an analysis of the number of entries and exits in each zone of interest, the number of saccades between each zone for each trial, the global/local ration (i.e., ratio proportion of large saccades/small saccades) and the pupil size. More details about this possible extension are available online (Grégoire et al., 2020; https://orbi.uliege.be/handle/2268/253756).

Extension to neuropsychological populations

Experimental studies presented in this thesis focused exclusively on healthy young and older adults. Nonetheless, in Study 1 and Chapter 3 of the Introduction, we showed several possible dissociations of RI in brain-injured patients. In the Introduction, we reviewed thirteen studies on RI in aphasic patients (Barde et al., 2010; Biegler et al., 2008; Hamilton & Martin, 2007a; Jefferies et al., 2007b; Jefferies & Lambon Ralph, 2006a; Kuzmina & Weekes, 2017; N. Martin & Saffran, 1992; R. C. Martin & Lesch, 1996; McCall et al., 2022; Nozari, 2019; T. T. Schnur et al., 2006; Tan & Martin, 2018; Thompson-Schill et al., 2002). Some of these studies showed selective RI deficits for phonological vs. semantic information even though these dissociations are not systematic and could reflect, at least partly, domain-specific WM impairment rather than domain-specific RI impairment (Barde et al., 2010; R. C. Martin & Lesch, 1996; McCall et al., 2022; T. T. Schnur et al., 2006). In addition, very few studies supported a dissociation of verbal versus visual RI abilities in brain-injured patients (Hamilton & Martin, 2005; Kuzmina & Weekes, 2017).

Examining the degree of dissociation or association between phonological, semantic, and visual RI abilities in patients with inferior frontal lesions with our well-matched RI paradigms across domains would bring critical evidence regarding the dissociability of RI abilities in neuropsychological populations and critical evidence for the domain-specificity of RI overall. Two studies addressing this question were planned in the present PhD thesis context. Unfortunately, due to the COVID-19 lock-down situation that had impacted a significant part of the data collection phase for this PhD thesis, the studies planned to be run on aphasic patients with language control deficits could not be completed.

Conclusion

This thesis investigated domain-generality vs. domain-specificity resistance-to-interference, particularly in aging. The research conducted across four studies on RI processes concludes that RI appears highly specific to the domain rather than exhibiting domain-general characteristics. Beforehand, we provided normative data for stimuli, ensuring consistency for subsequent experiments. Then, a preliminary literature review highlighted dissociations between visual, verbal phonological, and verbal semantic domains but cautioned against task disparities in comparing RI across domains. We also underlined the need to get a more robust statistical framework. Subsequently, we showed in two studies strong evidence for domain-specific RI with Bayesian statistics and an additional correlational methodology. Moreover, fMRI results revealed domain-specific effects in brain regions, with multivariate prediction analyses supporting this hypothesis. These findings underscore the importance of considering domain specificity when studying RI and call for further research with well-matched tasks to advance our understanding of this cognitive process.

Afterword

To complete this PhD thesis, I intended to report this work beyond the usual scientific community. Indeed, science popularization and science mediation play an essential role in disseminating scientific knowledge to a non-expert public. Popularization of science involves making science accessible and understandable to all, using clear language and concrete examples. Its outreach aims to transmit scientific knowledge interactively and engagingly, encouraging interaction with the public through experiments, demonstrations, and discussions. An example is science education, which is essential when introducing children to the world of science. From a young age, children are naturally curious and eager to discover. Popular science allows them to satisfy this curiosity by offering them accessible explanations adapted to their level of understanding. In that perspective, we submitted in November 2022 an article reviewed by a scientific mentor and children explaining the concepts of Hasher and Zacks (1988) more thoroughly. By exposing children to science fun and engagingly, science education stimulates their interest in the world around them and encourages them to ask questions, explore and experiment.

Wait! How we control our thoughts and actions at different ages

Coline Grégoire & Steve Majerus

Under review (2022). *Frontiers for Young Minds.*

Abstract. Your classmate cannot stop talking? You cannot avoid listening to your classmate when you should focus on your teacher? This is what inhibition is useful for! Inhibition is the ability to ignore, suppress and resist to irrelevant information coming from our environment or ourselves. Inhibition is more difficult for young kids, is optimal in young adults, and then becomes again more problematic when we are getting older. How does inhibition work? Why does inhibition change across age? Can we train inhibition? In this article, we will aim at answering these questions.

Keywords. Inhibition, Aging, Elderly, Prefrontal cortex, Brain, Control, Memory

What is Inhibition?

Imagine you are in your classroom, and you want to follow your teacher. In the meantime, you hear two of your friends whispering and another one typing on his/her phone under the table just next to you. In order to focus on your teacher's words, you need to mentally suppress the noise produced by your classmates, this is called inhibition or inhibitory control. More generally, inhibition* is the ability to suppress information that is not important or relevant for what you are currently doing or plan to do [1]. It allows you to think, learn, reason, remember and solve problems without being overwhelmed by too much information. It is also very important for controlling your body and emotions. You can consult "Stop! How we inhibit acts" from Nicole Swann and Ian Greenhouse for Frontiers Young Minds to get more information on the specific mechanism of how we inhibit physical actions such as stopping yourself from crossing a road when you hear a truck coming and honking.

In our lab, we are interested in the role of inhibition for memorizing and retrieving things in an accurate manner. Inhibition allows us to filter the things we are thinking about, or we are retrieving from memory. This filter has three functions (see Figure 1). The first one is "Access"* : inhibition can allow information to get access or not to our awareness. It helps us to focus on and to memorize the most relevant information and to ignore the many less relevant bits of information we t. The second function is "Deletion"*. It removes potentially distracting information that succeeded in accessing our mind, or information that is not important anymore. If you think about a lunch you had last week at school, you would remember the friends sitting on your table, maybe what you were eating if it was pretty good or pretty bad, but you would not remember the colour of your chair (unless this is very important for you). The third function is "Restraint"*;it allows to reduce strong but inappropriate responses, thoughts or behaviors such as yelling when you are playing video games while your siblings are asleep.

This figure shows the key functions of inhibition: access, delete, and restraint. Inhibition acts like a filter. Each of its functions act like a referee controlling each step of a football game. At the beginning of the game, the referee can deny access to the playground to a player who does not wear the regular garment. This is the Access function of inhibition. During the game, the referee can show the red card to a player whose game behavior is not appropriate anymore and who must leave the game. This illustrates the Delete function. And finally, the referee can show the yellow card to a player to indicate that s/he shows excessive behavior on the playground, this is the Restraint function.

Figure 1

A Schematic Representation of Inhibition.

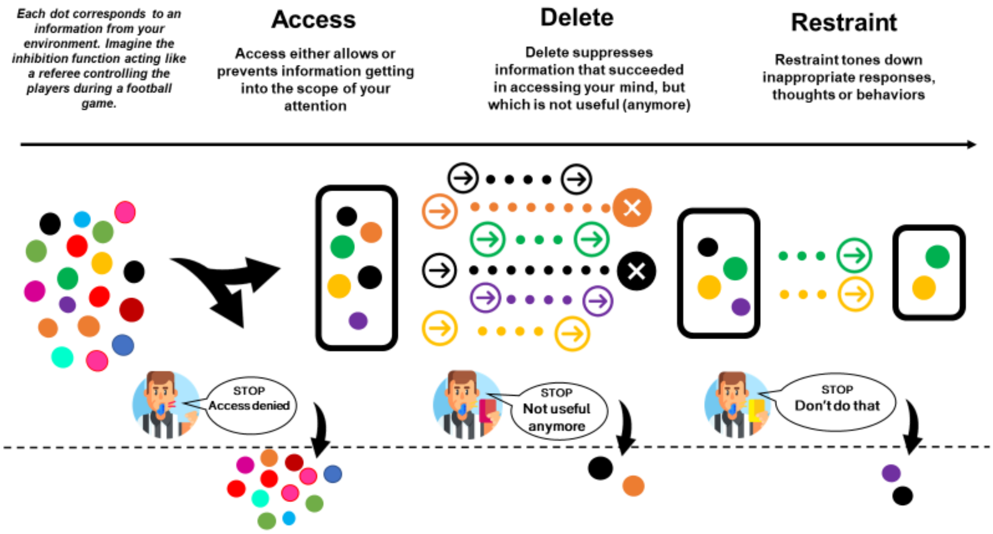
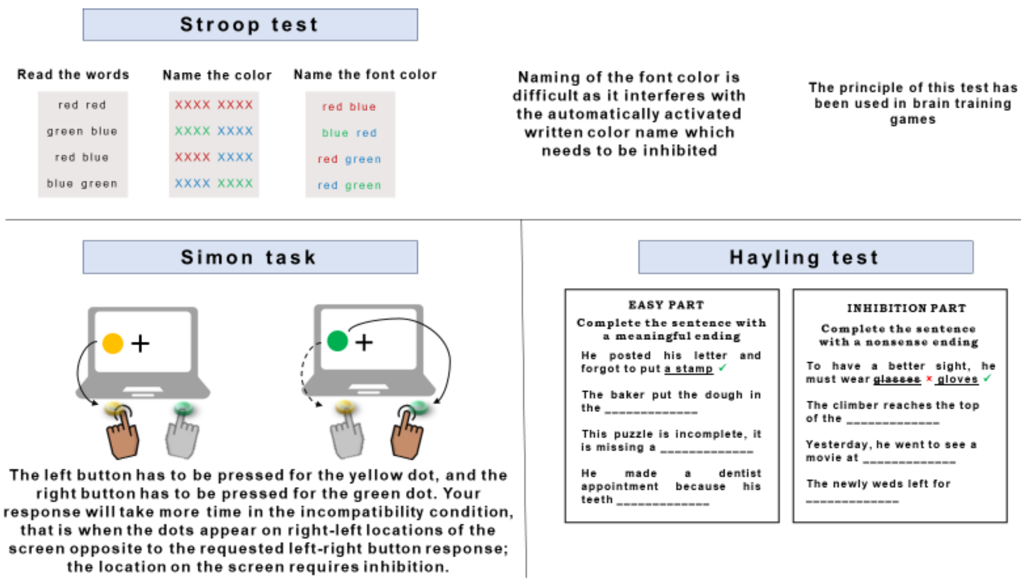


Figure 2

Examples of Tests Used to Measure Inhibition.



How do we measure inhibition?

There are many tasks that we use in the lab to measure inhibition. Three of them are displayed in Figure 2. On the top, the Stroop test is displayed. First, people have to read the words as fast and correctly as they can. Then, they have to name the color of the crosses. Finally, they must name the color of the font of the written words. In general, people have more difficulties to inhibit naming the colour word than the font color because they have to inhibit the automatic activation of the colour word that is written, this is called the Stroop effect. On the left bottom, the Simon task is displayed. People respond slower and less accurately if the location of the dot on the screen and the location of the response button do not match, this is called the Simon effect. On the right bottom, a verbal inhibition task is displayed. People tend to have difficulties in ending sentences with nonsense words if asked to; instead, they will want to produce the word that usually would complete the sentence.

"My grandpa can't stop talking" – How inhibition evolves with age.

Typically, inhibition emerges around the age of three or four years, becomes more and more efficient during childhood and adolescence, and is considered to be fully developed at early adult age. Thus, even if toddlers can show inhibition-like behavior from the first year of life, conscious use of inhibitory abilities only emerge progressively until reaching their optimal level at young adulthood.

But what happens at the other end of human development? As people get older and older, inhibition tends to decrease [2], potentially affecting everyday life behavior. In the lab, we compare young adults (18-40 years of age) and older adults (60-80 years of age) on different inhibition tasks such as the one presented in Figure 2. The scientific literature shows that elderly people can have more difficulties in these tasks [3]. For example, the Stroop effects can be increased, indicating difficulties in suppressing overlearned responses (such as reading a colour word; = a deficit for the previously mentioned "Delete" function). The Simon effect can also be more pronounced indicating difficulties to restrain a dominant motor response (= deficit in the "Restraint" function). Finally, older adults may have more difficulties to prevent irrelevant information to get access to their mind. For example, they may need more time to read a text if irrelevant words are added to the text as the irrelevant words will gain access to their mind even if they are asked not to read them (= deficit in "Access function"). In daily life, inhibition deficits can affect very simple behaviors. For example, we may buy apples instead of pears because we allow ourselves getting influenced by the advertisement put close to the apples in the shelf of the supermarket.

Deficits in inhibition can also interact with age-related declines in attention or in memory. We have explained above that inhibition works as a filter for the information to be stored and retrieved in your memory. When the filter starts working in a less appropriate manner, the wrong information may get selected, and people may in addition have difficulties in rejecting the wrongly retrieved information.

Why does inhibition become less efficient?

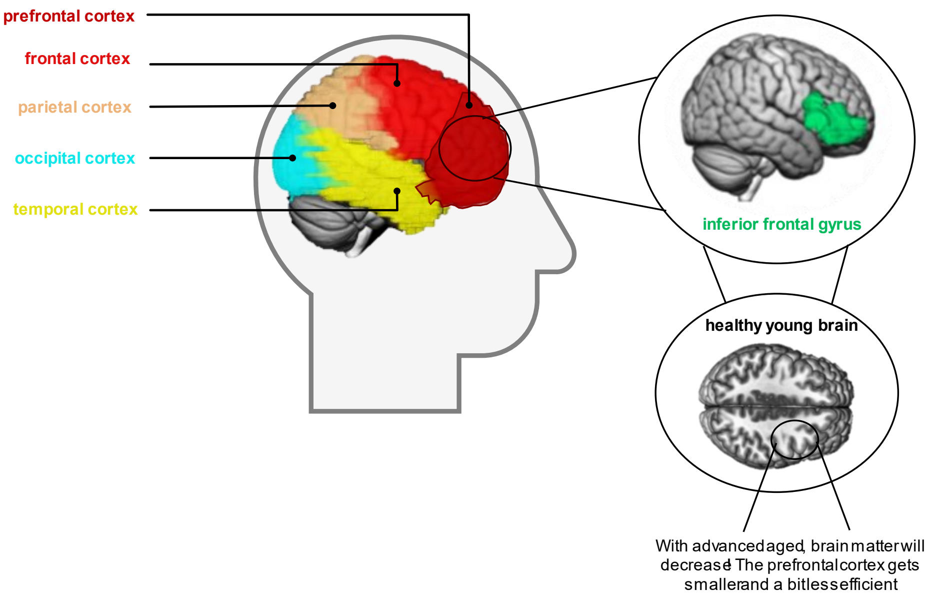
Many researchers in cognitive neurosciences* have examined the parts of the brain that are responsible for inhibition, in young and older adults. One way to study the brain is to use neuroimaging techniques such as functional magnetic resonance imaging (fMRI), you can check the article "How Is Magnetic Resonance Imaging Used to Learn About the Brain?" from Patricia Maria Hoyos, Na Yeon Kim, and Sabine Kastner in Frontiers Young Minds. Usually, researchers compare young and older adults as they perform inhibition tasks while their brain functioning is being measured by an MRI scanner. First, researchers have observed that the main part of the brain involved in inhibition is the inferior frontal gyrus [4], located in the prefrontal cortex*, see Figure 3. The prefrontal cortex exerts control over other parts of the brain, and it is involved in the three functions of inhibition mentioned previously. Second, researchers also have shown that this part of the brain is often underactivated in older adults compared to the younger adults. This underactivation means that this part of the brain is working a bit less efficiently compared to younger adults. But, why? Some studies show that the prefrontal cortex is getting smaller as we are getting older!

But not all aspects of inhibition are impacted by aging!

A recent study [5] compared 11 inhibition tasks similar to the ones presented in Figure 2. By using novel statistical methods, the researchers observed that the decline of inhibition is not homogenous across the different tasks or functions. For some tasks, there was even no difference between the younger and the older adults! Other scientists have shown that even if the prefrontal cortex shows less efficient functioning in elderly people, other parts of the brain may take the lead and compensate for the lesser prefrontal cortex efficiency! The good news is that aging is not an all-or-none process, it involved the recruitment of new neural and cognitive processing strategies to cope with the effects of ageing that affect some aspects of inhibition more than others.

Figure 3

The Main Parts of The Brain, with a Specific Focus on Prefrontal Cortex which Supports Inhibition.



On the left, you can see the main parts of the brain: the frontal, parietal, occipital and temporal cortices.

On the top right, you can see the prefrontal cortex and more specifically the inferior frontal gyrus. The inferior frontal gyrus is very closely involved in inhibition.

The right bottom panel, you can see a healthy young brain (top-view of the brain). The brain of elderly people is becoming thinner, therefore becoming a bit less efficient.

Glossary (*)

Access function: allow information to access or not to our awareness.

Delete function: removes potentially distracting information that succeeded in accessing your mind, or it removes information that is not important anymore

Restraint function: corresponds to reducing strong and inappropriate responses, thoughts or behaviors

Cognitive Neurosciences: Cognitive neuroscience is a multidisciplinary discipline linking cognitive sciences (cognitive psychology, psycholinguistics, neuropsychology, computational modelling) and neuroscience. It studies the neural structures and functions that support human cognition in order to understand how the brain gives rise to cognition, which in turn also furthers our understanding of cognition.

Inhibition: Inhibition involves controlling unwanted behavior, emotions, and thoughts by stopping them or by preventing them to occur.

Prefrontal Cortex: The Prefrontal Cortes is part of the Frontal lobe of the brain, one of the most developed brain structures in the human brain as compared to our primate cousins (e.g., chimpanzees, gorillas), and supports the regulation of complex cognitive, emotional, and behavioral functions.

Acknowledgments., This work was supported by Université de Liège: [Human Sciences Grant BSH-2018]. We thank Flaticon (https://www.flaticon.com/) – a database of free icons – for the referees and hand icons included in the Figures 1 and 2. The brain pictures from Figure 3 were designed on WFU_PickAtlas (https://www.nitrc.org/projects/wfu_pickatlas) and MRIcroGL (https://www.nitrc.org/projects/mricrogl/). Overall, the Figures were created by the first author on Microsoft Office Powerpoint.

Appendices

Appendix 1. Entire sets of stimuli for the phonological, semantic, and visual Similarity-Judgment tasks.

Appendix 2. Psycholinguistics variables controlled for each item for the semantic Similarity-Judgment tasks.

Appendix 3. Bayesian Independent Samples T-Test performed on the psycholinguistics variables between the facilitation and the interfering conditions of the semantic similarity-judgement task.

Appendix 4. Entire sets of stimuli for the phonological, and visual Recent-Negative Task.

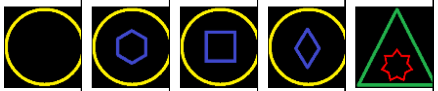
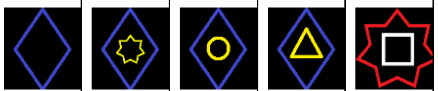
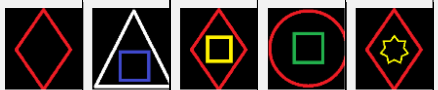
Appendix 5. Percentages of association between the items of each pair used in the semantic Recent-Negative task.

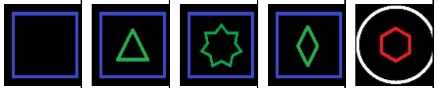
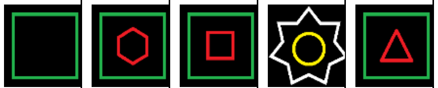
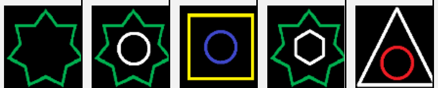
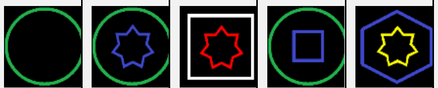
Appendix 6. Psycholinguistics variables controlled for each item for the semantic Recent-Negative task.

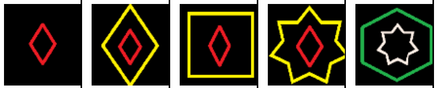
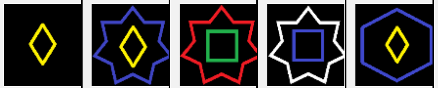
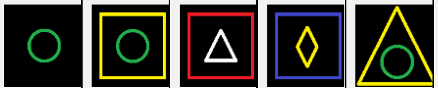
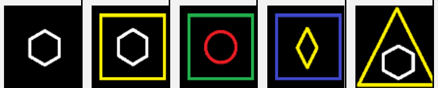
Appendix 7. Bayesian Independent Samples T-Test performed on the psycholinguistics variables within the pairs of the semantic Recent-Negative task.

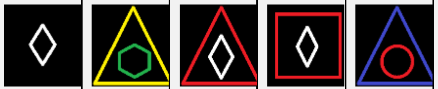
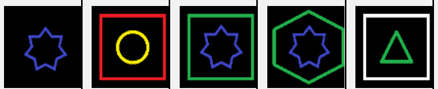
Table 1

Entire sets of stimuli for the phonological, semantic, and visual Similarity-Judgment tasks.

Visual judgment-similarity task																	
low control									high control								
essai	amorce	cible_1	cible_2	test_1	test_2	pos_test	correct_response	type	essai	amorce	cible_1	cible_2	test_1	test_2	pos_test	correct_response	type
f_01						left	z	1	i_01						left	z	1
f_02						left	z	1	i_02						left	z	1
f_03						left	z	1	i_03						left	z	1
f_04						left	z	1	i_04						left	z	1
f_05						left	z	1	i_05						left	z	1

f_06		left	z	1	i_06		left	z	1
f_07		left	z	1	i_07		left	z	1
f_08		right	o	1	i_08		right	o	1
f_09		right	o	1	i_09		right	o	1
f_10		right	o	1	i_10		right	o	1
f_11		right	o	1	i_11		right	o	1
f_12		right	o	1	i_12		right	o	1
f_13		right	o	1	i_13		right	o	1

f_14		left	z	2	i_14		left	z	2
f_15		left	z	2	i_15		left	z	2
f_16		left	z	2	i_16		left	z	2
f_17		left	z	2	i_17		left	z	2
f_18		left	z	2	i_18		left	z	2
f_19		left	z	2	i_19		left	z	2
f_20		right	o	2	i_20		right	o	2
f_21		right	o	2	i_21		right	o	2

f_22						right	o	2	i_22						right	o	2
f_23						right	o	2	i_23						right	o	2
f_24						right	o	2	i_24						right	o	2
f_25						right	o	2	i_25						right	o	2
f_26						right	o	2	i_26						right	o	2

Phonological judgment-similarity task															
low control								high control							
essai	amorce	cible_1	cible_2	test_1	test_2	pos_test	correct_response	essai	amorce	cible_1	cible_2	test_1	test_2	pos_test	correct_response
f_01	rimu	biré	fizé	varo	libu	right	o	i_01	muzi	muza	ruka	mazu	zéfa	right	o
f_02	tura	luma	futa	zibé	rova	right	o	i_02	rive	ruvé	kuké	révu	muza	right	o

f_03	kamu	léfu	zétu	varu	bilé	left	z	i_03	zira	zivu	tivu	vuzi	mélu	right	o
f_04	rozi	motu	tozu	lori	béra	left	z	i_04	tola	véba	téla	talé	zéfi	right	o
f_05	lufa	mira	zila	tuva	béko	left	z	i_05	zobu	tizu	zibu	zubi	rivé	right	o
f_06	kebu	réfi	méti	téku	balo	left	z	i_06	ruli	zumé	rulé	rélu	boké	right	o
f_07	zite	komé	folé	vuba	rifé	right	o	i_07	kelo	kalo	ramo	kola	vati	right	o
f_08	bilo	kuro	fumo	méta	lizo	right	o	i_08	foza	lomi	fomi	fimo	buri	right	o
f_09	mebi	zébu	télu	vora	béfi	right	o	i_09	vuzi	vuzo	furo	mélo	vozu	left	z
f_10	zifu	kimé	tilé	viku	bora	left	z	i_10	zuvo	zuvé	kulé	bimé	zévu	left	z
f_11	lume	futa	kula	zori	buvé	right	o	i_11	rume	rumo	bumo	laro	romu	left	z
f_12	latu	rako	malo	bavu	zéfi	left	z	i_12	rilo	malo	ralo	lavu	rola	left	z
f_13	fubi	rali	mati	ruvi	zébo	left	z	i_13	reka	vofa	roka	lomi	rako	left	z
f_14	leto	zimo	rifo	buka	véko	right	o	i_14	vuro	vuri	kufi	viru	zéti	right	o
f_15	lifu	timo	zilo	méra	biku	right	o	i_15	kefi	luti	kufi	vuzo	kifu	left	z
f_16	rila	lofa	moba	tiva	kuzé	left	z	i_16	mave	foté	mové	mévo	boku	right	o
f_17	talo	fati	rabi	zako	mévu	left	z	i_17	muke	vuta	muka	bova	maku	left	z
f_18	zobi	vufi	muki	labé	tori	right	o	i_18	kuta	bila	kita	rifo	kati	left	z

f_19	ziru	kifo	milo	tivu	béka	left	z	i_19	toli	bubi	tuli	luza	tilu	left	z
f_20	malo	rito	fivo	zéku	lafo	right	o	i_20	fori	bomu	foru	ravu	furo	left	z
f_21	fabu	zifu	kiru	valu	métu	left	z	i_21	zuve	buka	zuva	zavu	fita	right	o
f_22	mota	bofu	loru	zoka	véli	left	z	i_22	zimu	zimé	vifé	kolé	zémi	left	z
f_23	tofa	zuma	muka	roza	rité	left	z	i_23	ruva	ruvi	kuzi	rivu	tofi	right	o
f_24	fumi	rubé	luté	tova	zuki	right	o	i_24	tufi	tofi	tovi	tifu	fomé	right	o
f_25	fezo	méba	léka	rilu	véfo	right	o	i_25	bila	bilo	mizo	tivé	mozi	left	z
f_26	lazi	béfi	méri	tobu	raki	right	o	i_26	fabu	fébu	téru	vémo	fubé	left	z

Semantic judgment-similarity task															
low control								high control							
essai	amorce	cible_1	cible_2	test_1	test_2	pos_test	correct_response	essai	amorce	cible_1	cible_2	test_1	test_2	pos_test	correct_response
f_01	boue	crapaud	marécage	vase	consonne	left	z	i_01	animal	grue	bâtiment	chantier	oiseau	left	z
f_02	pepin	souci	ennui	problème	mousse	left	z	i_02	papier	feuille	automne	châtaigne	page	left	z

f_03	timbre	collection	enveloppe	poste	biscuit	left	z	i_03	attache	saxophone	trombone	orchestre	épingle	left	z
f_04	chocolat	gâteau	biscuit	éclair	vis	left	z	i_04	explosion	grenade	cerise	fraise	bombe	left	z
f_05	course	vitesse	saut	élan	répertoire	left	z	i_05	mer	pompier	sirène	chant	feu	left	z
f_06	vol	délit	cambriolage	brigand	poster	left	z	i_06	ecole	faculté	possibilité	capacité	université	left	z
f_07	alphabet	consonne	voyelle	lettre	saut	left	z	i_07	environnement	centre	milieu	côté	culture	left	z
f_08	index	répertoire	livre	sommaire	marécage	left	z	i_08	chateau	bouche	palais	goût	manoir	left	z
f_09	blaireau	mousse	barbe	rasoir	délit	left	z	i_09	theatre	copie	réplique	imitation	dialogue	left	z
f_10	avocat	justice	juge	tribunal	poster	left	z	i_10	chant	sirène	son	pompier	mer	left	z
f_11	clou	perceuse	vis	cheville	partition	left	z	i_11	esprit	muguet	pensée	géranium	rêve	left	z
f_12	note	musique	partition	sol	justice	left	z	i_12	agilite	adresse	lieu	maison	habileté	left	z
f_13	mur	affiche	poster	punaise	saut	left	z	i_13	benefice	cuisine	recette	farine	argent	left	z

f_14	cheville	vis	clou	souci	perceuse	right	o	i_14	horoscope	cancer	maladie	signe	tumeur	right	o
f_15	enveloppe	poster	collection	marécage	timbre	right	o	i_15	habilete	maison	adresse	agilité	lieu	right	o
f_16	sol	partition	note	délit	musique	right	o	i_16	epingle	trombone	orchestre	attache	saxophone	right	o
f_17	lettre	voyelle	alphabet	vis	consonne	right	o	i_17	culture	milieu	côté	environnement	centre	right	o
f_18	elan	saut	course	collection	vitesse	right	o	i_18	page	châtaigne	feuille	papier	automne	right	o
f_19	ennui	problème	souci	biscuit	pépin	right	o	i_19	bombe	fraise	grenade	explosion	cerise	right	o
f_20	vase	marécage	boue	partition	crapaud	right	o	i_20	reve	pensée	géranium	esprit	muguet	right	o
f_21	barbe	rasoir	mousse	répertoire	blaireau	right	o	i_21	dialogue	réplique	imitation	théâtre	copie	right	o
f_22	cambriolage	brigand	délit	collection	vol	right	o	i_22	signe	tumeur	cancer	horoscope	maladie	right	o
f_23	livre	sommaire	répertoire	souci	index	right	o	i_23	manoir	palais	goût	château	bouche	right	o
f_24	eclair	biscuit	chocolat	consonne	gâteau	right	o	i_24	universite	capacité	faculté	école	possibilité	right	o

f_25	punaise	poster	mur	justice	affiche	right	o	i_25	oiseau	chantier	grue	animal	bâtiment	right	o
f_26	justice	tribunal	juge	mousse	avocat	right	o	i_26	argent	recette	farine	bénéfice	cuisine	right	o

Table 2
Psycholinguistics variables controlled for each item for the semantic similarity-judgement task.

items	mean freq	log(mean freq)	nbr_lettre	nbr_syllabe	voisorth	voisphon	puorth	puphon	Imageability	Concretness
adresse	55,6	1,74507479	7	2	3	1	7	5	2,91860465	4,06976744
affiche	6,88	0,83758844	7	2	2	6	7	4	4,67441861	4,58139535
agilité	2,155	0,33344727	7	4	0	1	5	5	2,53488372	2,93023256
alphabet	3,765	0,57576498	8	3	0	0	7	6	4,19767442	4,19767442
animal	42,06	1,62386927	6	3	2	0	6	6	4,51162791	4,59302326
argent	354,68	2,5498367	6	2	4	7	6	4	4,70930233	4,31395349
attache	2,905	0,46314614	7	2	2	5	7	4	3,24418605	3,86046512
automne	29,925	1,47603416	7	2	0	4	7	4	3,88372093	3,93023256
avocat	56,8	1,75434834	6	3	0	2	6	5	4,65116279	4,44186047
barbe	35,55	1,55083961	5	1	9	12	5	4	4,91860465	4,79069767
bâtiment	21,33	1,32899086	8	3	1	4	5	6	4,74418605	4,74418605
bénéfice	6,175	0,79063696	8	3	0	1	8	7	2,18604651	2,97674419
biscuit	3,76	0,57518785	7	2	0	0	7	6	4,84883721	4,84883721
blaireau	2,67	0,42651126	8	2	0	1	7	5	4,54651163	4,56976744
bombe	31,85	1,50310944	5	1	4	8	5	3	4,61627907	4,52325581
bouche	177,695	2,24967521	6	1	9	23	6	3	4,95348837	4,74418605
boue	33,695	1,52756546	4	1	18	28	4	2	4,54651163	4,65116279
brigand	1,725	0,2367891	7	2	0	8	7	5	4,01162791	4,13953488
cambriolage	4,315	0,6349808	11	4	0	0	9	9	3,69767442	4,13953488
cancer	15,56	1,19200959	6	2	6	8	6	5	2,70930233	3,81395349
capacité	8,9	0,94939001	8	2	1	2	8	5	2,06976744	2,62790698
centre	66,73	1,82432113	6	1	7	11	6	4	3,37209302	3,24418605

cerise	3,03	0,48144263	6	2	1	2	6	5	4,96511628	4,90697674
chant	23,01	1,36191662	5	1	2	24	5	2	3,74418605	3,79069767
chantier	12,535	1,09812434	8	2	1	11	7	4	4,44186047	4,24418605
châtaigne	0,715	-0,14569396	9	2	1	2	9	5	4,75581395	4,76744186
château	51,945	1,71554375	7	2	0	16	7	4	4,81395349	4,77906977
cheville	8,89	0,94890176	8	2	2	1	8	5	4,8372093	4,74418605
chocolat	29,175	1,46501087	8	3	0	0	8	6	4,90697674	4,81395349
clou	8,995	0,95400117	4	1	4	7	4	3	4,85957592	4,84302326
collection	18,935	1,27726531	10	3	0	3	10	8	3,46511628	3,81395349
consonne	0,135	-0,86966623	8	2	0	3	7	5	3,34883721	4,24418605
copie	12,665	1,10260519	5	2	3	8	5	4	3,56976744	4,09302326
côté	373,97	2,57283676	4	2	4	28	4	4	2,84883721	3,53488372
course	45,835	1,66119724	6	1	7	13	6	4	4,03488372	3,80232558
crapaud	7,84	0,89431606	7	2	0	3	7	5	4,84883721	4,77906977
cuisine	104,195	2,01784688	7	2	2	0	7	6	4,68604651	4,58139535
culture	21,54	1,3332457	7	2	0	0	7	6	2,68604651	2,87209302
délit	8,85	0,94694327	5	2	8	9	5	4	2,44186047	3,08139535
dialogue	14,285	1,15488025	8	2	1	0	8	5	2,95348837	3,04651163
éclair	14,47	1,16046853	6	2	0	1	6	5	4,67441861	4,05813954
école	162,775	2,2115877	5	1	4	6	5	4	4,70930233	4,37209302
élan	21,09	1,32407658	4	2	4	16	4	3	3,93023256	3,76744186
ennui	26,5	1,42324587	5	2	1	3	5	4	2,46511628	2,63953488
enveloppe	18,81	1,2743888	9	3	2	0	9	6	4,88372093	4,70930233
environnement	6,355	0,80311556	13	5	0	0	13	9	2,8255814	3,11627907
épingle	6,105	0,78568567	7	2	2	0	7	5	4,65116279	4,69767442

esprit	157,27	2,19664589	6	2	0	0	6	5	2,36046512	2,51162791
explosion	20,375	1,30909762	9	3	0	1	8	8	4,59302326	4,22093023
faculté	9,89	0,99519629	7	3	0	0	7	7	2,96511628	2,60465116
farine	10,72	1,03019479	6	2	4	5	6	5	4,80232558	4,81395349
feu	207,63	2,3172901	3	3	9	24	3	2	4,76183311	4,13178295
feuille	29,795	1,47414339	7	1	3	9	7	3	4,8372093	4,61627907
fraise	4,6	0,66275783	6	1	1	10	6	4	4,93023256	4,88372093
gâteau	28,125	1,44909253	6	2	1	13	5	4	4,93023256	4,76744186
géranium	0,86	-0,06550155	8	3	0	0	6	5	4,38372093	4,59302326
goût	87,655	1,94277669	4	1	3	26	4	2	2,39534884	3,12790698
grenade	6,405	0,80651913	7	2	1	2	7	6	4,74418605	4,38372093
grue	3,19	0,50379068	4	1	3	11	4	3	4,67441861	4,65116279
habileté	6,285	0,79830528	8	4	1	1	7	6	2,01162791	2,56976744
horoscope	1,875	0,27300127	9	3	0	0	4	4	3,53488372	3,30232558
imitation	4,505	0,6536948	9	4	0	1	8	6	2,77906977	3,26744186
index	17,305	1,2381716	5	2	1	0	5	5	4,08139535	3,91860465
juge	43,1	1,63447727	4	1	6	8	4	3	3,91860465	4,29069767
justice	48,59	1,6865469	7	2	0	1	7	6	2,69767442	2,68604651
lettre	124,835	2,09633637	6	1	2	11	6	4	4,65116279	4,51162791
lieu	183,25	2,26304398	4	1	8	13	4	3	2,94186047	3,20930233
livre	132,095	2,12088638	5	1	7	5	5	4	4,86046512	4,8372093
maison	515,925	2,71258657	6	2	2	8	6	4	4,89534884	4,8372093
maladie	50,885	1,70658978	7	3	1	0	7	6	2,75581395	3,52325581
manoir	7,46	0,87273883	6	2	0	2	5	4	4,61627907	4,63953488
marécage	173,02	2,23809631	3	1	0	0	8	7	4,3372093	4,45348837

mer	0,155	-0,8096683	6	2	11	30	3	3	4,77756498	4,3372093
milieu	157,645	2,1976802	6	2	0	3	5	5	3,1627907	3,12790698
mousse	14,64	1,16554108	6	1	7	19	6	3	4,47674419	4,30232558
muguet	2,115	0,32531037	6	2	0	5	6	3	4,73255814	4,73255814
mur	115,735	2,06346472	3	1	11	22	3	3	4,84883721	4,76744186
musique	139,345	2,14409139	7	2	1	2	7	5	3,74418605	3,93023256
note	36,37	1,5607433	4	1	15	22	4	3	4,34883721	3,6627907
oiseau	45,875	1,66157608	6	2	2	6	6	4	4,8372093	4,81395349
orchestre	15,875	1,20071373	9	2	2	0	9	7	4,62790698	4,61627907
page	40,52	1,60766944	4	1	15	20	4	3	4,54651163	4,60465116
palais	44,135	1,64478313	6	2	8	30	5	4	4,59302326	4,45348837
papier	100,455	2,00197156	6	2	4	8	6	5	4,76744186	4,6627907
partition	3,3	0,51851394	9	3	0	1	8	7	4,3372093	4,38372093
pensée	62,585	1,79647026	6	2	4	18	5	4	2,3372093	2,44186047
pépin	3,135	0,49623755	5	2	3	5	5	4	4,67441861	4,37209302
perceuse	0,585	-0,23284413	8	2	2	2	0	0	4,75581395	4,73255814
pompier	1,84	0,26481782	7	2	1	6	6	5	4,8372093	4,8255814
possibilité	18,125	1,25827802	11	5	0	0	7	6	1,74418605	2,67441861
poste	73,11	1,86397678	5	1	8	4	5	4	3,73652531	3,84302326
poster	1,305	0,11561051	6	2	6	7	6	5	4,17441861	4,18604651
problème	223,2	2,34869419	8	2	0	0	6	6	2,13953488	2,97674419
punaise	1,585	0,20002927	7	2	1	0	7	5	4,59302326	4,51162791
rasoir	11,895	1,07536445	6	2	2	2	4	4	4,8372093	4,79069767
recette	8,225	0,91513591	7	2	2	10	5	5	3,94186047	4,3255814
répertoire	3,69	0,56702637	10	3	0	0	8	7	3,62790698	4,11627907

réplique	9,465	0,97612062	8	2	2	1	8	6	2,09302326	3,26744186
reve	89,795	1,95325216	4	1	5	13	4	3	3,26744186	2,58139535
saut	13,895	1,14285855	4	1	6	23	4	2	4,41860465	4,37209302
saxophone	1,26	0,10037055	9	3	0	0	9	7	4,70930233	4,77906977
signe	93,465	1,97064901	5	1	9	16	5	3	3,3372093	3,39534884
sirène	9,2	0,96378783	6	2	1	2	4	4	4,47674419	4,18604651
sol	97,07	1,98708503	3	1	13	20	3	3	4,40697674	4,39534884
sommaire	0,275	-0,56066731	8	2	0	8	8	5	3,58139535	3,93023256
son	44,505	1,64840881	3	1	17	26	3	2	2,61627907	3,53488372
souci	33,265	1,52198753	5	2	2	9	5	4	2,04651163	2,68604651
theatre	52,415	1,71945559	7	2	0	0	7	5	4,58139535	4,43023256
timbre	7,5	0,87506126	6	1	1	1	6	4	4,83618331	4,77906977
tribunal	25,175	1,40096948	8	3	1	0	8	8	4,18604651	4,36046512
trombone	1,16	0,06445799	8	2	1	2	8	6	4,69767442	4,69767442
tumeur	3,99	0,6009729	6	2	4	3	5	4	2,89534884	4,04651163
université	25,73	1,41043979	10	5	0	0	10	10	4,44186047	4,3372093
vase	18,295	1,26233241	4	1	9	17	4	3	4,84794802	4,81395349
vis	6,52	0,8142476	3	1	21	22	3	3	4,69767442	4,72093023
vitesse	46,24	1,66501783	7	2	0	0	5	4	2,8255814	3,40697674
vol	57,68	1,76102525	3	1	9	15	3	3	3,65116279	3,48837209
voyelle	0,415	-0,3819519	7	2	0	0	5	5	3,6627907	4,20930233

Table 3.
Bayesian Independent Samples T-Test performed on the psycholinguistics variables between the facilitation and the interfering conditions of the semantic similarity-judgement task.

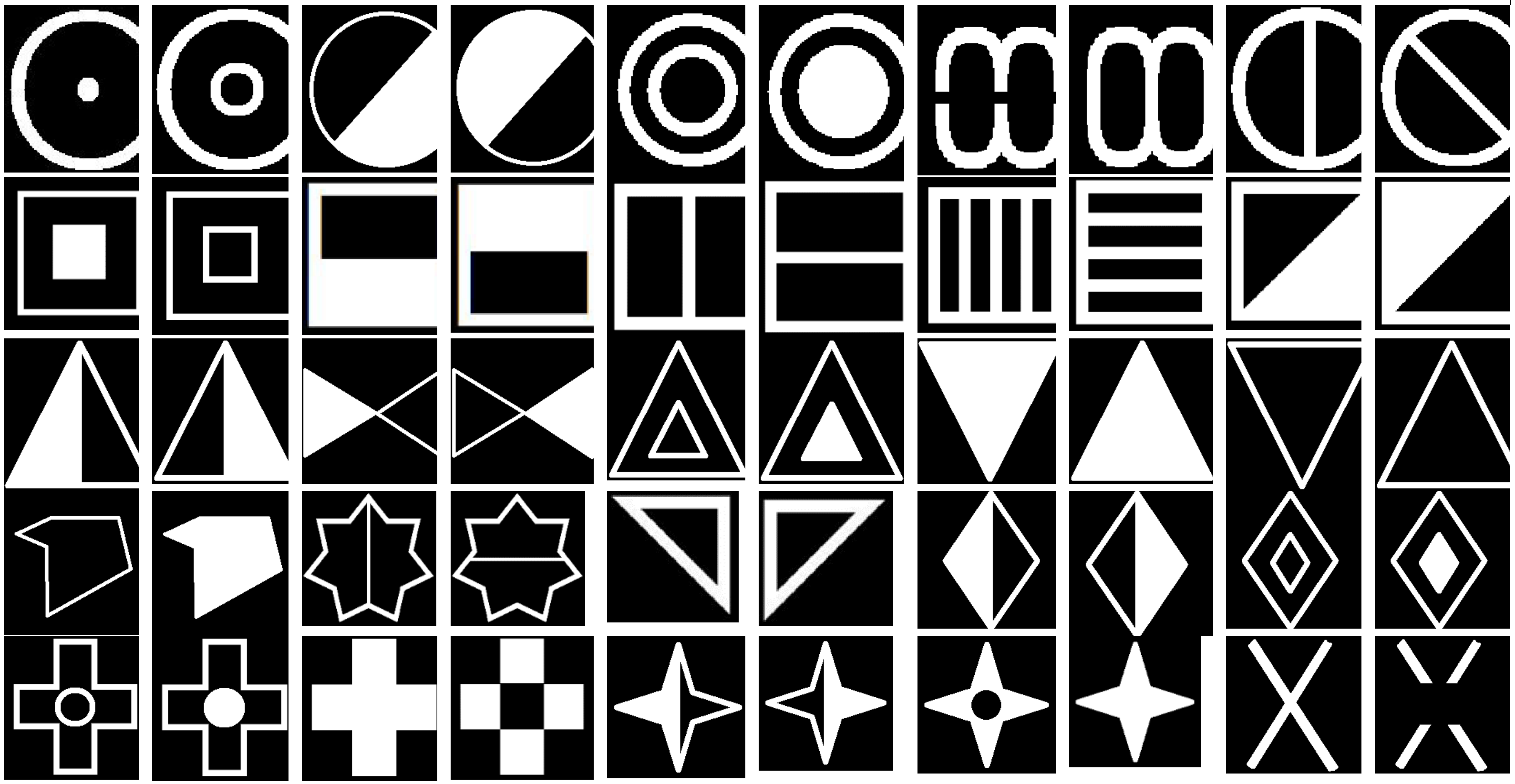
	BF_{01}	BF_{10}
log(mean frequency)	3.461	0.289
nbr_lettre	2.072	0.483
nbr_syllabe	0.907	1.103
voisorth	2.811	0.356
voisphon	4.832	0.207
puorth	2.907	0.344
puphon	4.503	0.222
Imageability	1.086	0.921
Concreteness	1.093	0.915

Notes. Mean frequency integrates the films and books frequencies.

Table 4

Entire sets of stimuli for the phonological, and visual Recent-Negative Task. See Tables 5 for semantic variables.

Visual material



Phonological material with International Alphabetical Phonetic

P01	kaoul	/kaul/	gaoul	/gaul/
P02	chemas	/ʃəmas/	jemas	/ʒəmas/
P03	chesai	/ʃəzɛ/	nesai	/nəzɛ/
P04	chonla	/ʃɔ̃la/	jonla	/ʒɔ̃la/
P05	chuvis	/ʃyvis/	puvis	/pyvis/
P06	dondi	/dɔ̃di/	londi	/lɔ̃di/
P07	gouad	/guad/	douad	/duad/
P08	grega	/gRəga/	crega	/kRəga/
P09	lezer	/ləzɛr/	tezer	/təzɛr/
P10	lenfeu	/lãfø/	menfeu	/mãfø/
P11	neucles	/nøklɛs/	veucles	/vøklɛs/
P12	pateurs	/patœRs/	rateurs	/RatœRs/
P13	plilan	/plilã/	blilan	/blilã/
P14	qiande	/kjãdə/	guiande	/gjãdə/
P15	peussu	/pœsy/	feussu	/fœsy/
P16	tepé	/təpe/	depé	/dəpe/
P17	tiage	/tjaʒə/	diage	/djaʒə/
P18	tomlan	/tɔmlã/	domlan	/dɔmlã/
P19	tomvi	/tɔmvi/	domvi	/dɔmvi/
P20	marou	/maRu/	barou	/baRu/
P21	tumèr	/tymɛR/	dumèr	/dymɛR/
P22	vièlpe	/vjɛlpə/	pièlpe	/pjɛlpə/
P23	vouma	/vuma/	nouma	/numa/
P24	zufmé	/zyfme/	sufmé	/syfme/
P25	tougé	/tuʒe/	dougé	/duʒe/

Table 5

Percentages of association between the items of each pair used in the semantic Recent-Negative task.

item1	item2	%association
album	photo	92,1
ampoule	lumière	59,5
arc	flèche	57,3
bateau	mer	43,8
briquet	feu	49,4
brosse	cheveux	41,5
café	tasse	39,5
chien	chat	48,3
collier	perle	41,5
couteau	fourchette	49,4
gorille	singe	33,7
horloge	heure	55
laitue	salade	69,7
moufle	gant	43,8
moulin	vent	41,5
pneu	voiture	48,3
poire	pomme	22,5
poste	timbre	60,7
raquette	tennis	88,7
rateau	pelle	39,3
reveil	matin	55
ruche	abeille	82

serrure	clef	70,7
ski	neige	47,2
vase	fleur	63

From: Ferrand, L., & Alario, F.-X. (1998). Normes d'associations verbales pour 366 noms d'objets concrets. *L'Année psychologique*, 98(4), 659-709. https://doi.org/10.3406/psy.1998.28564

Table 6

Psycholinguistics variables controlled for each item for the semantic Recent-Negative task.

ortho	phon	meanfreq	log(meanfreq)	nbsyll	nblettres	voisorth	voisphon	puorth	puphon	Imageability	Concretness
album	albOm	11,335	1,054421524	2	5	0	2	5	5	4,27058824	4,45348837
ampoule	@pul	8,145	0,910891089	2	7	1	3	7	4	4,90588235	4,80232558
arc	aRk	9,285	0,967781908	1	3	5	12	3	3	4,78823529	4,36046512
bateau	bato	83,885	1,923684309	2	6	0	17	6	4	4,87058824	4,80232558
briquet	bRikE	11,14	1,046885191	2	7	5	10	7	5	4,83529412	4,80232558
brosse	bROs	11,65	1,066325925	1	6	5	8	6	4	4,84705882	4,69767442
café	kafe	156,245	2,193806128	2	4	6	19	4	4	4,82352941	4,54651163
chien	Sj5	138,205	2,140523755	1	5	3	12	5	3	4,97647059	4,81395349
collier	kolje	16,295	1,212054365	2	7	2	8	6	4	4,89411765	4,79069767
couteau	kuto	47,67	1,678245152	2	7	0	10	7	4	4,95294118	4,8255814
gorille	goRij	2,79	0,445604203	2	7	3	3	4	4	4,88235294	4,8372093
horloge	ORlOZ	11,68	1,067442843	2	7	0	0	7	5	4,88235294	4,8255814
laitue	lety	1,795	0,254064453	2	6	0	3	5	4	4,71764706	4,75581395
moulin	mul5	11,205	1,049411861	2	6	0	9	6	4	4,8	4,6627907
pneu	pn2	5,285	0,723044992	1	4	1	4	4	3	4,90588235	4,8255814
poire	pwaR	8,24	0,915927212	1	5	8	13	5	4	4,88235294	4,8255814
poste	pOst	73,11	1,863976784	1	5	8	4	5	4	3,73652531	3,84302326
raquette	RakEt	1,73	0,238046103	2	8	5	10	6	5	4,88235294	4,6627907
rateau	Rato	1,195	0,077367905	2	6	1	16	5	4	4,4	4,77
réveil	RevEj	22,19	1,346157302	2	6	0	2	6	5	4,4	4,18604651
ruche	RyS	2,335	0,368286885	1	5	8	15	5	3	4,70588235	4,72093023
serrure	seRyR	11,74	1,069668097	2	7	1	2	7	5	4,72941177	4,72093023

ski	ski	9,42	0,974050903	1	3	4	6	3	3	4,76470588	4,48837209
vase	vaz	18,295	1,262332414	1	4	9	17	4	3	4,84794802	4,81395349
abeille	abEj	3,355	0,525692525	2	7	0	3	4	4	4,89411765	4,86046512
chat	Sa	58,485	1,767044494	1	4	7	26	4	2	4,95294118	4,90697674
cheveux	S°v2	189,67	2,277998644	2	7	1	4	0	4	4,81176471	4,77906977
clef	kle	25,11	1,399846713	1	4	1	11	4	3	4,89411765	4,68604651
feu	f2	207,63	2,317290104	1	3	9	24	3	2	4,76183311	4,13178295
flèche	flES	11,875	1,074633618	1	6	3	9	3	4	4,81176471	4,55813954
fleur	fl9R	34,085	1,532563298	1	5	1	6	5	4	4,90588235	4,76744186
fourchette	fuRSEt	7,965	0,90118578	2	10	0	0	9	6	4,91764706	4,81395349
gant	g@	8,915	0,950121348	1	4	4	26	4	2	4,81176471	4,8255814
heure	9R	427,63	2,631068165	1	5	3	10	5	2	2,87058824	2,94186047
lumière	lymjER	177,335	2,248794459	2	7	1	1	5	4	3,90588235	3,46511628
matin	mat5	320,96	2,506450911	2	5	11	20	5	4	2,98823529	3,09302326
mer	mER	173,02	2,238096308	1	3	11	30	3	3	4,77756498	4,3372093
moufle	mufl	0,31	-0,508638306	1	6	2	3	6	4	4,70588235	4,80232558
neige	nEZ	56,225	1,749929464	1	5	2	10	5	3	4,76470588	4,53488372
pelle	pEl	10,05	1,002166062	1	5	9	26	5	3	4,91764706	4,74418605
perle	pERl	5,715	0,757016235	1	5	11	12	5	4	4,65882353	4,60465116
photo	foto	88,565	1,947262127	2	5	1	11	5	4	4,65882353	4,62790698
pomme	pOm	32,925	1,517525784	1	5	9	16	5	3	4,95294118	4,88372093
salade	salad	15,645	1,194375567	2	6	4	6	6	5	4,91764706	4,77906977
singe	s5Z	18,295	1,262332414	1	5	5	7	5	3	4,91764706	4,8372093
tasse	tas	21,795	1,338356873	1	5	14	29	5	3	4,91764706	4,84883721
tennis	tenis	12,305	1,090081618	2	6	3	3	6	5	4,44705882	4,30232558

timbre	t5bR	7,5	0,875061263	1	6	1	1	6	4	4,83618331	4,77906977
vent	v@	139,57	2,144792078	1	4	13	27	4	2	3,42352941	3,6627907
voiture	vwatyR	305,01	2,484314078	2	7	3	2	7	6	4,91764706	4,8372093

Table 7
Bayesian Independent Samples T-Test performed on the psycholinguistics variables within the pairs of the semantic Recent-Negative task.

	BF_{10}	BF_{01}
Log(Mean frequency)	2.259	0.443
nbsyll	1.440	0.694
nblettres	0.346	2.892
voisorth	0.905	1.105
voisphon	0.858	1.166
puorth	0.615	1.626
puphon	0.755	1.325
Imageability	0.466	2.145
Concretness	0.679	1.472

Notes. Mean frequency integrates the films and books frequencies.

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