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

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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, Funding acquisition.

LA: Conceptualization, Methodology, Resources, Writing - review & editing.

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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 older 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

1. Introduction

Resistance-to-interference (RI) is a cognitive control process that involves selectively attending to relevant information while inhibiting the processing of irrelevant information (Dempster & Corkill, 1999; Harnishfeger, 1995; Miyake et al., 2000). RI is also an essential concept in models of memory and attentional control, where it is often discussed in the context of inhibitory control (e.g., Boen et al., 2022; Huster et al., 2020) and executive function (Diamond, 2013; Miyake & Friedman, 2012).

Some authors make a distinction between the interference aspect itself, which would be the reason leading to decreased or slowed performance in the presence of irrelevant information while inhibition would refer to the observed performance decrement itself (Dempster, 1995; Werner & Parks, 2022). Inhibition however can also refer to specific inhibitory mechanisms at the level of neural transmission (A. R. Aron, 2007; Dillon & Pizzagalli, 2007 for reviews). In order to avoid further conceptual confusion, some authors have therefore proposed to use the concept of RI or inhibitory control rather than inhibition (Dempster, 1993; Grégoire & Majerus, 2023; Lustig et al., 2001; Munakata et al., 2011; Oberauer et al., 2004; Werner & Parks, 2022). More generally, control of interference is also a major aspect of many theories of working memory and attentional control (Engle, 2002; Engle & Kane, 2003; Lewandowsky et al., 2008; Oberauer & Lin, 2017). Furthermore, RI is an essential concept for understanding cognitive aging. Age-related declines in cognitive function are often attributed to difficulties at the level executive control, including RI (Hasher & Zacks, 1988; Lustig et al., 2007). This decline is reflected in older adults' increased difficulty in ignoring irrelevant information, as evidenced by a number of studies and paradigms (Anderson et al., 2000; Anderson & Spellman, 1995; Demonty et al., 2022; Kuhlmann et al., 2021). Difficulties in RI are also a central feature of the Interference Theory of cognitive in aging (Hasher & Zacks, 1988; Lustig et al., 2007; Weeks et al., 2020). More recent versions have proposed that older adults may have low-resolution and noisy representations of incoming and target information, leading to increased sensorimotor interference and thus decreased cognitive performance (see Mille et al., 2021, 2023 for reviews).

At the neural level, RI has been associated with the involvement of the inferior frontal gyrus (IFG) across different tasks and sensory modalities. However, 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 systematically investigates the neural substrates supporting RI across phonological, semantic, and visual domains. Furthermore, it systematically investigates the neural substrates supporting RI across phonological, semantic, and visual domains, 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; 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. However, 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 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 built 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, 2007; Jefferies et al., 2007; Schnur et al., 2006, 2009; 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 for investigating visual RI may also involve verbal RI processes, given that verbal labels can be associated quite easily to 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 occluding 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 provided a systematic investigation of the neural substrates of RI abilities across visual, phonological, and semantic domains, by using structurally equivalent task designs as well as univariate and multivariate analysis methods.

Furthermore, we contrasted the neural substrates associated with RI in young vs. older participants in order to assess the question of the domain-specificity of RI processes in the most sensitive manner. 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; Burke & Osborne, 2007; Campbell et al., 2020; 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 (e.g. visual: 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; Li et al., 2001; Reuter-Lorenz et al., 2001; Reuter-Lorenz & Park, 2014; Sebastian et al., 2013).

The present study provides a systematic investigation of 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 (Snyder et al., 2007; Thompson-Schill et al., 1997), with a recent adaptation to phonological RI (Attout et al., 2022). We further adapted the paradigm for including a visual RI condition. The task required participants to choose the test-item that provides the closest association with two target-items, after 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 in terms of task structure. 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. older adults). 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 (i.e., young adults: 20-40 years old; older adults: 60-80 years old) in order to ensure that 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, older adults had higher receptive vocabulary knowledge (see Table 1). Those were confirmed with the Bayesian informative hypotheses evaluation Welch's T-Test. All the older 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 had been approved by the local ethics committee (Comité d'Ethique Hospitalo-Facultaire Universitaire de Liège; file number: B707201939419). The data from six older participants and one young adult had to be excluded due to technical difficulties during fMRI acquisition. The final sample size was comprised of 34 young adults (19 men, 15 women) and 29 older adults (13 men, 16 women).

Table 1

Participant characteristics (mean and standard deviation).

	Groups	**N**	**Mean**	**SD**	**SE**	**Bayesian T-Test**	**Bain Welch T-Test**
Level of	Young	34	15.44	1.96	0.34	BF_{10} = 0.39	BF_{10} = 0.21

education	adults					$BF_{01} = 2.55$	$BF_{01} = 4.35$
	Older adults	29	14.97	1.80	0.33		
Age	Young adults	34	25.09	3.72	0.64	$BF_{10} =$ 1.02+6	$BF_{10} =$ 5.25+8
	Older adults	29	67.55	5.47	1.02		
Vocabulary level	Young adults	34	24.47	2.87	0.49	$BF_{10} =$ 2.07+39	$BF_{10} =$ 8.23+27
	Older adults	29	29.31	2.88	0.53		

Note. Bayesian T-Test were performed between both groups for each variable. BF_{01} are displayed when $BF_{10} < 3$.

Similarity-Judgment Task

Material

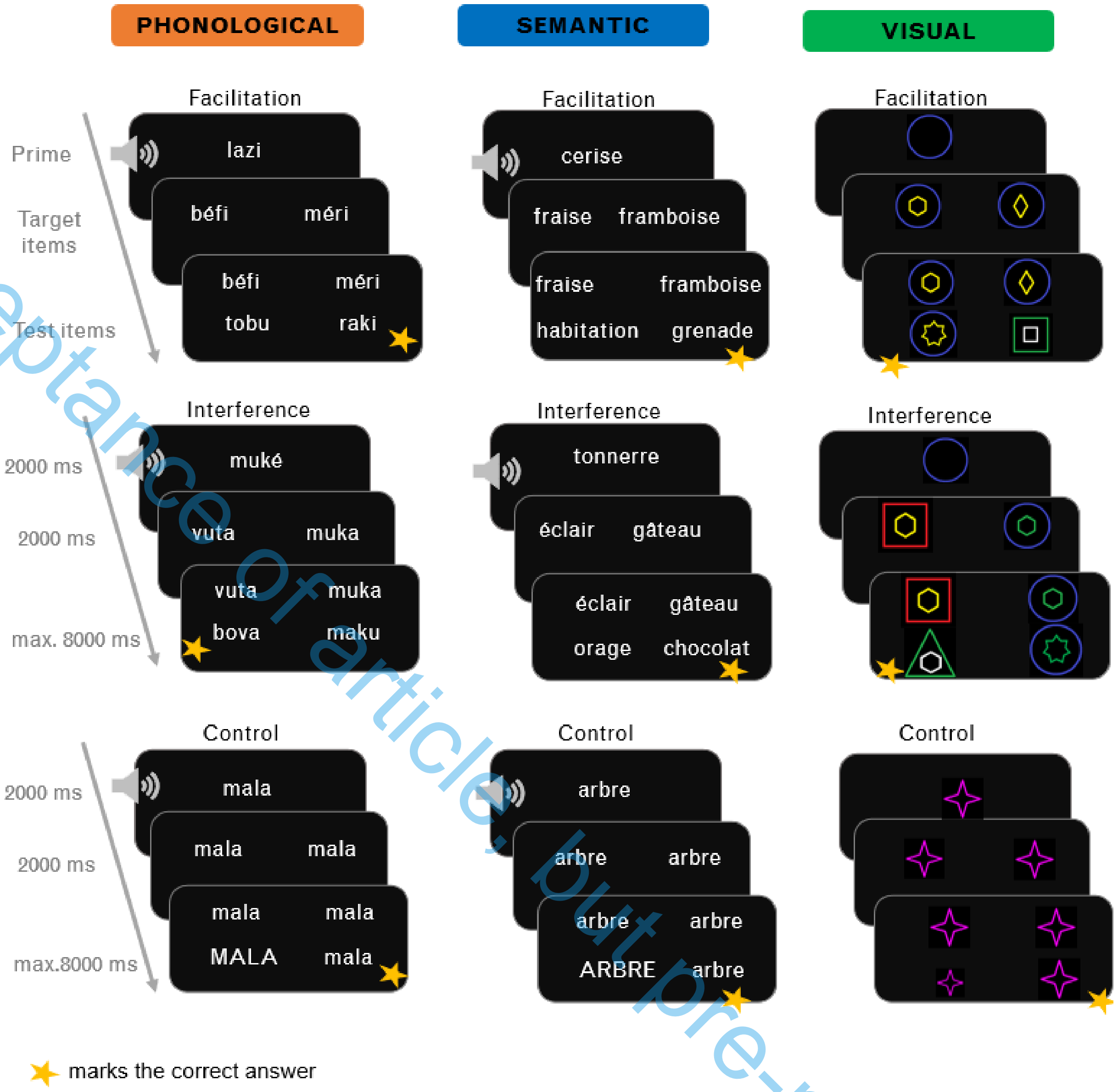
Phonological domain. The phonological similarity-judgment task required participants to match nonwords on a specific criterion. Participants were asked to choose the test nonword that was most close to both target nonwords, i.e., sharing a vowel in the same position. In the RI condition, the prime nonword, 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). 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 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 thunderbolt" 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} = [0.207 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 Lexique database (New et al., 2001, 2004) while concreteness, imageability, and emotional valence were taken from a database developed by Grégoire et al. (in press).

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.



Procedure

Prior to the experiment, the participants were given a practice session outside the magnetic resonance environment to familiarize themselves with the task requirements. Original instructions were: “*Vous allez d'abord voir une figure ou entendre un mot ou un non-mot. Regardez ou écoutez bien. Puis, vous allez voir 2 autres figures ou mots ou non-mots s'afficher en haut de l'écran. Regardez-les bien ou lisez-les bien. Deux autres figures/mots/non-mots vont s'ajouter en bas de l'écran. Vous devez choisir lequel des 2 est le plus similaire (colle le mieux) aux DEUX figures/mots/non-mots du haut de l'écran. Appuyez* *sur la touche (gauche/droite) de la figure, du mot ou non-mot retenu, le plus rapidement possible*.”, which in English is: “First, you'll see a figure or hear a word or non-word. Look at them or listen to them carefully. Then you'll see 2 more figures or words or non-words appearing at the top of the screen. Look at them or read them carefully. Two more figures/words/non-words will then appear at the bottom of the screen. You must choose which of the 2 is most similar (fits best) to the TWO figures/words/non-words at the top of the screen. Press the (left/right) key corresponding to the chosen figure, word or non-word, as quickly as possible”. This practice session included ten practice trials for each domain separately, then 10 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-weigthed structural brain scan was acquired after the task, as described below. The task was presented on a workstation that ran Matlab 15 and the the Cogent 2000 toolbox (Cogent 2000; RRID:SCR_015672; http://www.vislab.ucl.ac.uk/cogent_2000.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 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). For each task, there were 26 facilitation trials, 26 RI trials and 10 control trials. Right and left correct responses had the same probability. All task domains and conditions were presented in the same session, by fully randomly mixing task domains and conditions rather than presenting the task domains in blocks (as in Attout et al., 2022). This specific procedure was used to avoid strategic and habituation effects for a specific domain if all trials of a given task domain were presented in a block. Note that participants were informed about the task domain of the upcoming trial, via the presentation of the label “visual”, “phonological”, or “semantic” written in white capital letters on the middle of the black screen before the start of each trial. The duration of the intertrial interval was variable (random Gaussian distribution centered on a mean duration of 7000 ± 1000 ms) and further varied as a function of the participants’ response times since the probe array disappeared immediately after a response was recorded. 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. 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 and preprocessing

Image 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), for which field maps for distortion correction of the echo-planar images (EPI) were generated. 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).

Image Preprocessing. 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 mapping from subject to Montreal Neurological Institute space was estimated from the structural image with the "unified segmentation" approach (Ashburner & Friston, 2005). The warping parameters were then separately applied to the functional and structural images to produce normalized images of resolution 2×2×2 mm3 and 1×1×1 mm3, respectively. Finally, the warped functional images were spatially smoothed with a Gaussian kernel of 5 mm full-width at half-maximum to improve signal-to-noise ratio while preserving the underlying spatial distribution (Schrouff et al., 2012). This smoothing also diminishes the impact that residual head motion can have on MVPA performance, even after head motion correction (Gardumi et al. 2016). We screened for excessive head motion by excluding an entire participant's data set if their movement throughout the session exceeded 4 mm or 4°, or if there was a peak movement greater than 3 mm or 3° relative to the initial head position. We opted for a 4 mm / 4° threshold for whole session movement, rather than the more common 3 mm / 3° threshold, due to the extended duration of the entire set of tasks in the scanner, which increases the likelihood of significant movement over the session. This screening process resulted in the exclusion of the data of four participants.

Data analysis

For behavioural analyses and multivariate fMRI 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 $BF_{10} = 1.29 \times 10^{12}$. Finally, for the 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. For each participant 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 the resistance to interference is required. On this basis, for each domain, two linear regressors were performed, one for the interfering condition and another for the facilitation condition, resulting in six linear regressors 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 1 plus white noise. After the first smoothing (5-mm FWHM Gaussian kernel), the contrast images (for Interference – Facilitation images) were then entered in a second-level (random effects) across subjects 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 ($P_{corrected}<.05$ at the cluster-level) was applied to the contrasts of interests (Eklund et al., 2016). Conjunction analyses testing the conjunction null hypothesis (Friston et al., 2005) were 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. There was no further adaptation for HRF delay and HRF overlap given that HRF response is already modeled in the beta images. For within-domain classifications of RI level, a leave-one-trial-out cross-validation procedure was used 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. In addition, within-domain and between-domain statistical classifier performance was furthermore assessed at the individual level using Bayesian binominal tests which determined above chance-level individual classification accuracy thresholds with $BF_{10} > 3$. Finally, data visualizations for the multivariate analyses were performed in R Studio (R 3.3.0+) with R (4.03.0).

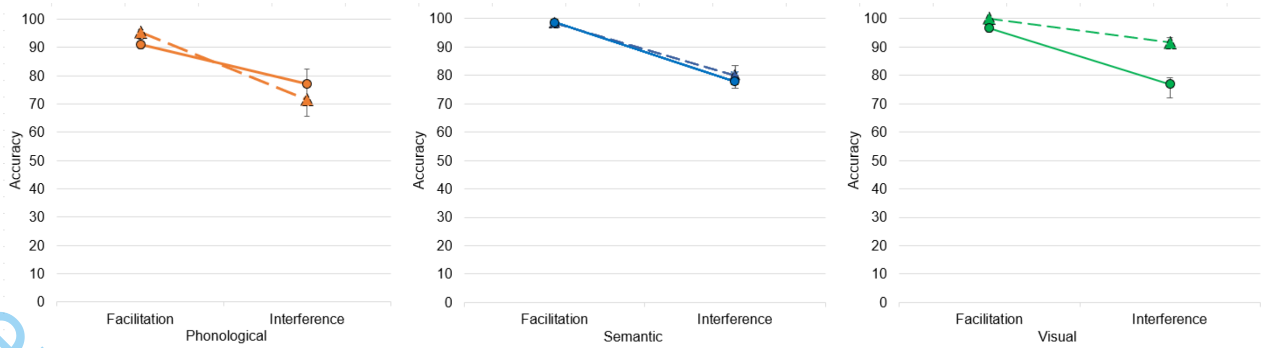
Results

Behavioral Analyses

A first 2 (Group: Young adults, Older 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 ($\eta^2_p = .11$) and Condition ($\eta^2_p = .60$) variables. This model was 2.56 more likely than the second one that included the same factors as well as the Group factor and the interaction between Domain and Group; hence the more parsimonious model should be preferred (see Methods section for further details on Bayesian evidence and the Bayesian model comparison approach). As expected, Bayesian post-hoc tests showed that accuracy was higher in the Facilitation condition compared to the Interference condition (BF_{10}= 6.29e+10). Post-hoc tests also revealed higher accuracy in the Visual domains compared to the Phonological domain ($BF_{10} = 60.98$), 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 ($BF_{10} = 0.78$; $BF_{01} = 1.28$). Note that performance in the Control conditions was not further analyzed as it reached ceiling level as expected (all accuracies > 97%).

Figure 2

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

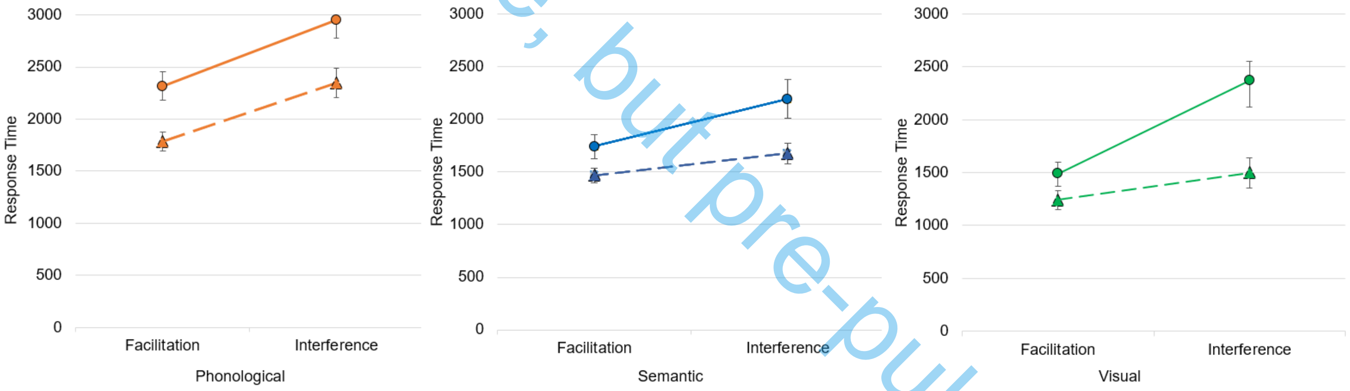


Note. --▲ : Young adults, -● : Older adults. Horizontal bars indicate standard errors.

Another 2 (Group: Young adults, Older adults) × 2 (Condition: Facilitation, Interference) × 3 (Domain: Phonological, Semantic, Visual) Bayesian Repeated Measures ANOVA was performed on the response times for correct answers. 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 older group (BF_{10} = 22.86). The post-hoc tests also showed that responses were faster in the Facilitation condition compared to the Interference 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 difference 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 older group (Domain effect: Young: η^2_p = .52. Older: 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 older group. The interaction between Group and Condition shows that the older group was slightly more impacted by the Interference conditions than the younger group (Condition effect: Young: η^2_p = .57; Older: η^2_p = .68). Lastly, the triple interaction reveals that the older 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: η^2_p = .61; Semantic: η^2_p = .26; Visual: η^2_p = .20; older adults: Phonological: η^2_p = .74; Semantic: η^2_p = .47; Visual: η^2_p = .52).

Figure 3

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



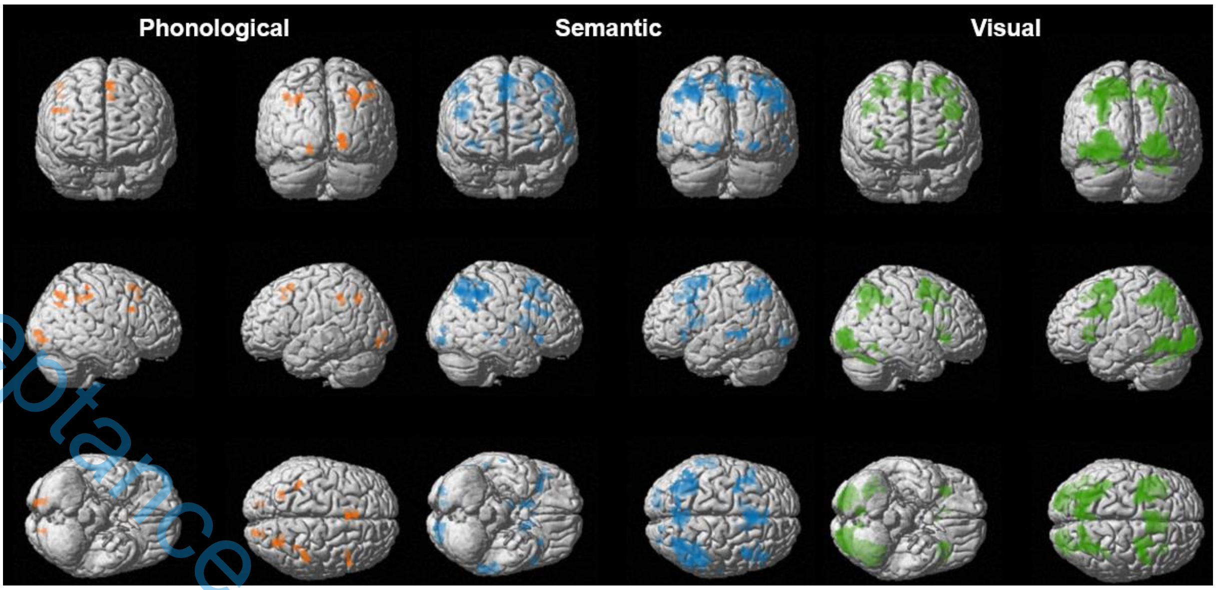
Note. --▲ : Young adults, -● : Older adults. Horizontal bars indicate standard errors.

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 (younger adults, older adults). 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 older 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 including in addition middle and superior frontal gyri as well as bilateral occipital gyri. When contrasting the different domains (see Table 3), there was only 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 older group were associated with activity foci mainly in the right angular and middle/superior occipital gyri. However, when contrasting the two age groups (by running a null conjunction analysis over the age groups contrasts for the three domains), no significant activity differences between the two groups were revealed.

Figure 4

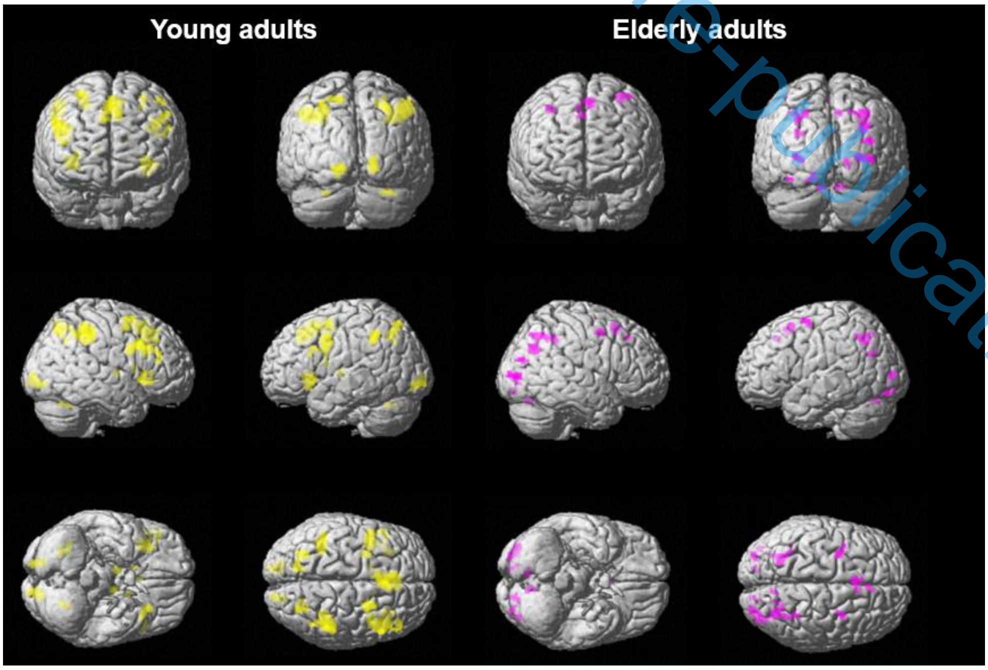
Univariate Activity Peaks for RI vs. Facilitation Condition Contrasts, as a Function of Task Domain.



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.

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.

Table 2

Univariate Results for Group and Task Domain Effects on RI Contrasts and Their Interaction (ANOVA).

Anatomical regions	**ANOVA**							
	BA area	No. Voxels	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* ≥ 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 × 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						
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	-12	6	14	5.31	5.52
Caudate		137	R	12	8	14	5.17	5.37
Simple effect of phonological RI[a]		FWEc: *k* ≥ 66						
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: $k \geq 94$						
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: $k \geq 68$						
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 Older adults[b]		FWEc: *k* ≥ 72						
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 [a], no voxel survived								
Phonological RI > Visual RI [a]**,** no voxel survived								
Semantic RI > Phonological RI [a]								
Semantic RI > Visual RI [a], no voxel survived								
Visual RI > Semantic RI [a], no voxel survived								
Visual RI > Phonological RI [a]		FWEc: *k* ≥ 120						
Superior parietal lobule	7	120	L	-28	-58	48	4.12	4.22
Young > Older[b], no voxel survived								
Older > Young[b]**, 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 older participants. b: null conjunction over relevant contrasts in phonological, semantic, and visual domains.

Multivariate analyses

Whole-Brain Multivariate Classifications Analyses

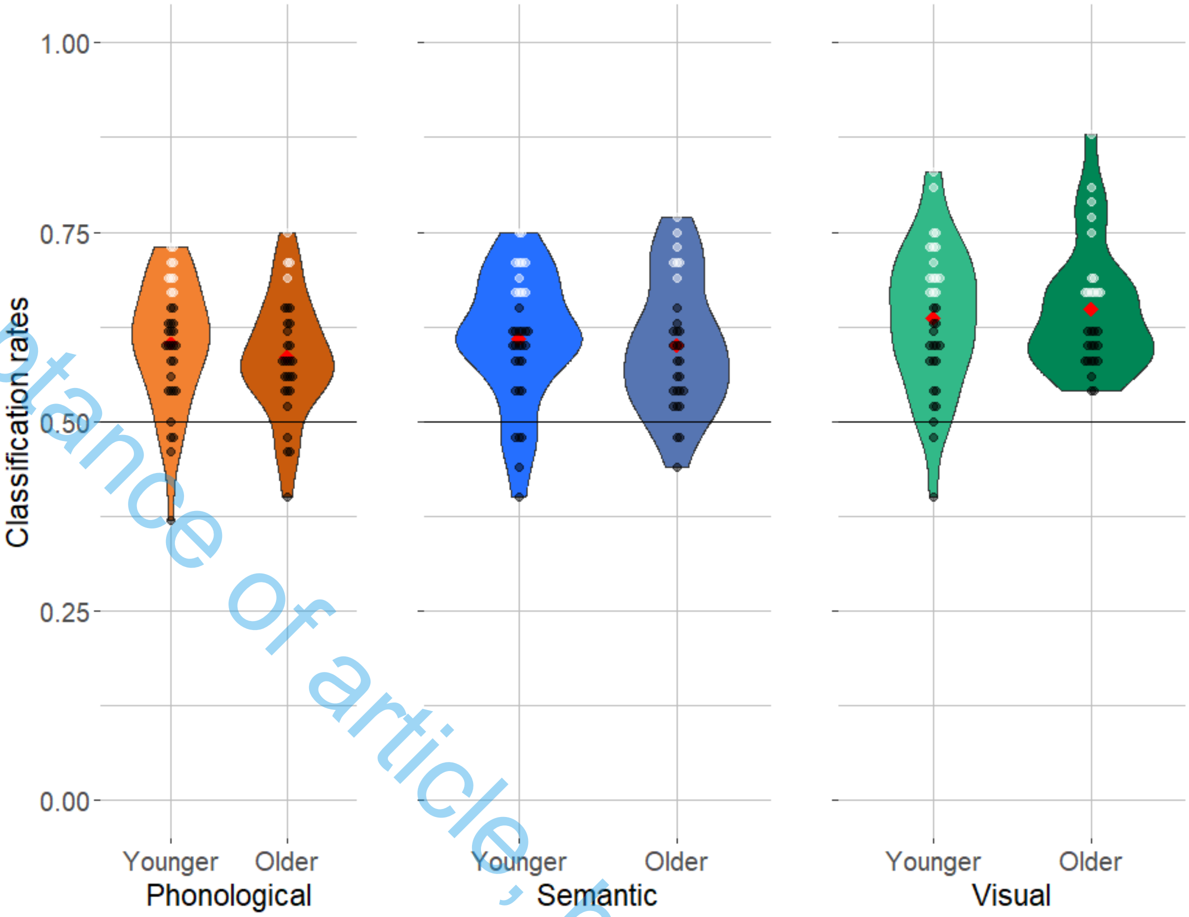
A first set of multivariate analyses assessed between-condition (RI vs. facilitation) classifications within each task domain at the whole-brain level. By performing Bayesian one-sample t-test, we observed reliable classification of the RI vs. facilitation conditions for each group and each task domain (see Figure 6 and Table 4; phonological: BF_{10} = 712763 for young adults, BF_{10} = 9854.01 for older adults; semantic: BF_{10} = 1.36e+6 for young adults, BF_{10} = 30244.35 for older adults; visual: BF_{10} = 1.72e+7 for young adults, BF_{10} = 4.40e+7 for older adults). These results were further explored via a 3 (domain) × 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. Note that the results remained unaffected by task difficulty, when included as covariates, as mean task accuracy performances. The model associated with the strongest evidence (BF_{10} = 3.25) solely included the Domain main effect. Moreover, Bayesian binomial tests indicated that 41%, 38%, and 44% of younger adults showed individual above-chance level classification (> 65%) of interference vs. facilitation conditions for phonological, semantic, and visual domains, respectively (see Figure 6). As for the older adults, 44%, 28%, and 52% of them presented above-chance level classifications (> 65%) for the phonological, semantic, and visual domains, respectively.

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 older adults) except for the right IFG pars orbitalis when examining classifications in the semantic domain for the older group ($BF_{10} = 1.56$; $BF_{01} = 0.64$), see Table 4 and Figure 7. When performing a 3 (domain) × 2 (hemisphere) × 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 on the open access repository.

Figure 6

Classification Rates at Whole-Brain level 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: older adults; Vivid Blue: young adults; Dark blue: older adults; Vivid Green: young adults; Dark green: older adults. White dots represent individual-level classification > .65 (with $BF_{10} > 3$) while black dots represent individual-level classification < .65. Red dots represent the mean.

Table 4

Bayesian One-Sample T-Test Values for the Within-Domain Classification of RI vs. Facilitation Conditions in Young and Older Adults at the Whole-Brain and ROI Levels.

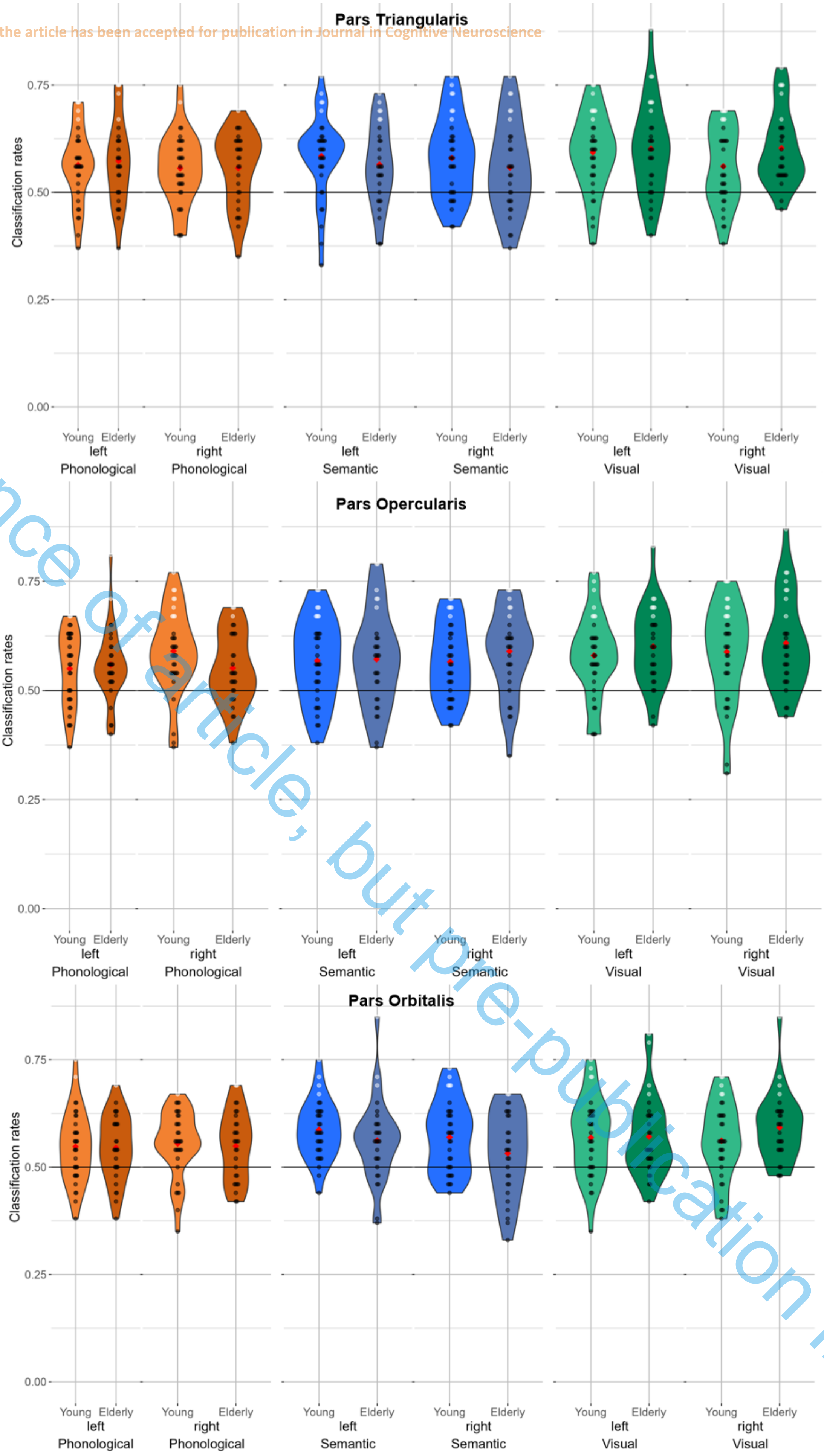
	Domain	Younger adults	Older adults
		BF_{10}	BF_{10}
Whole-Brain			
	Visual	**1.72e+7**	**4.40e+7**

		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 7

Classification Rates for RI vs. Facilitation Conditions, as a Function of Group, ROI, and Type of Domain.


Pars Triangularis
Classification rates
0.00
0.25
0.50
0.75
Young
Elderly
left
Phonological
right
Phonological
left
Semantic
right
Semantic
left
Visual
right
Visual
Pars Opercularis
Classification rates
0.00
0.25
0.50
0.75
Young
Elderly
left
Phonological
right
Phonological
left
Semantic
right
Semantic
left
Visual
right
Visual
Pars Orbitalis
Classification rates
0.00
0.25
0.50
0.75
Young
Elderly
left
Phonological
right
Phonological
left
Semantic
right
Semantic
left
Visual
right
Visual

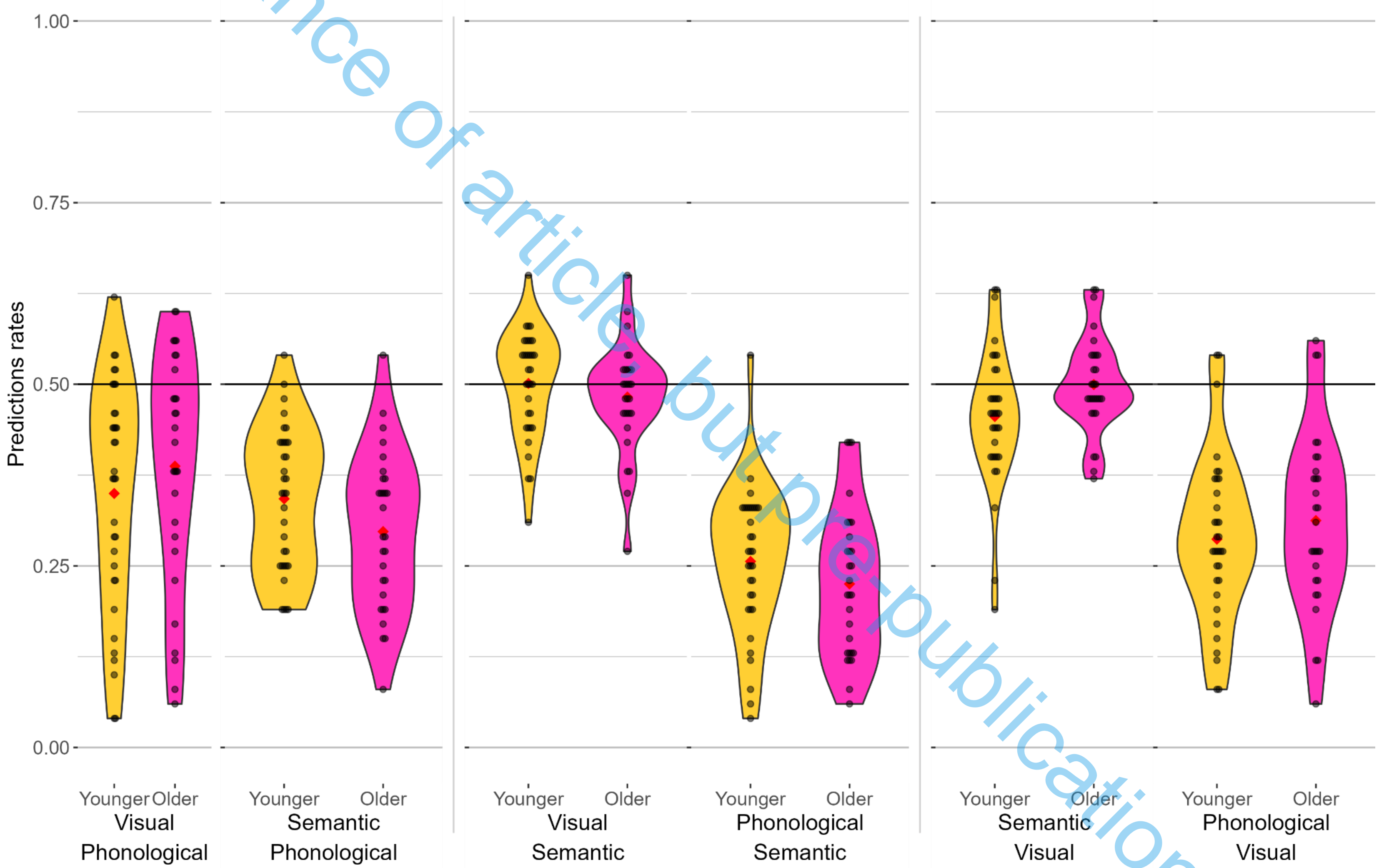
Note. From to bottom: Pars Triangularis, Pars Opercularis, and Pars Orbitalis. Vivid orange: young adults; Dark orange: older adults; Vivid Blue: young adults; Dark blue: older adults; Vivid Green: young adults; Dark green: older adults. The black line marks chance-level classification rate (0.5, 50%). White dots represent individual-level classification > .65 (with $BF_{10} > 3$) while black dots represent individual-level classification < .65. Red dots represent the mean.

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. No individual classification accuracy reached the above chance-level classification threshold. 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, see Figure 9. Similar, although slightly less reliable results, were also observed for the older group (BF_{10} = 2.37 and 2.08).

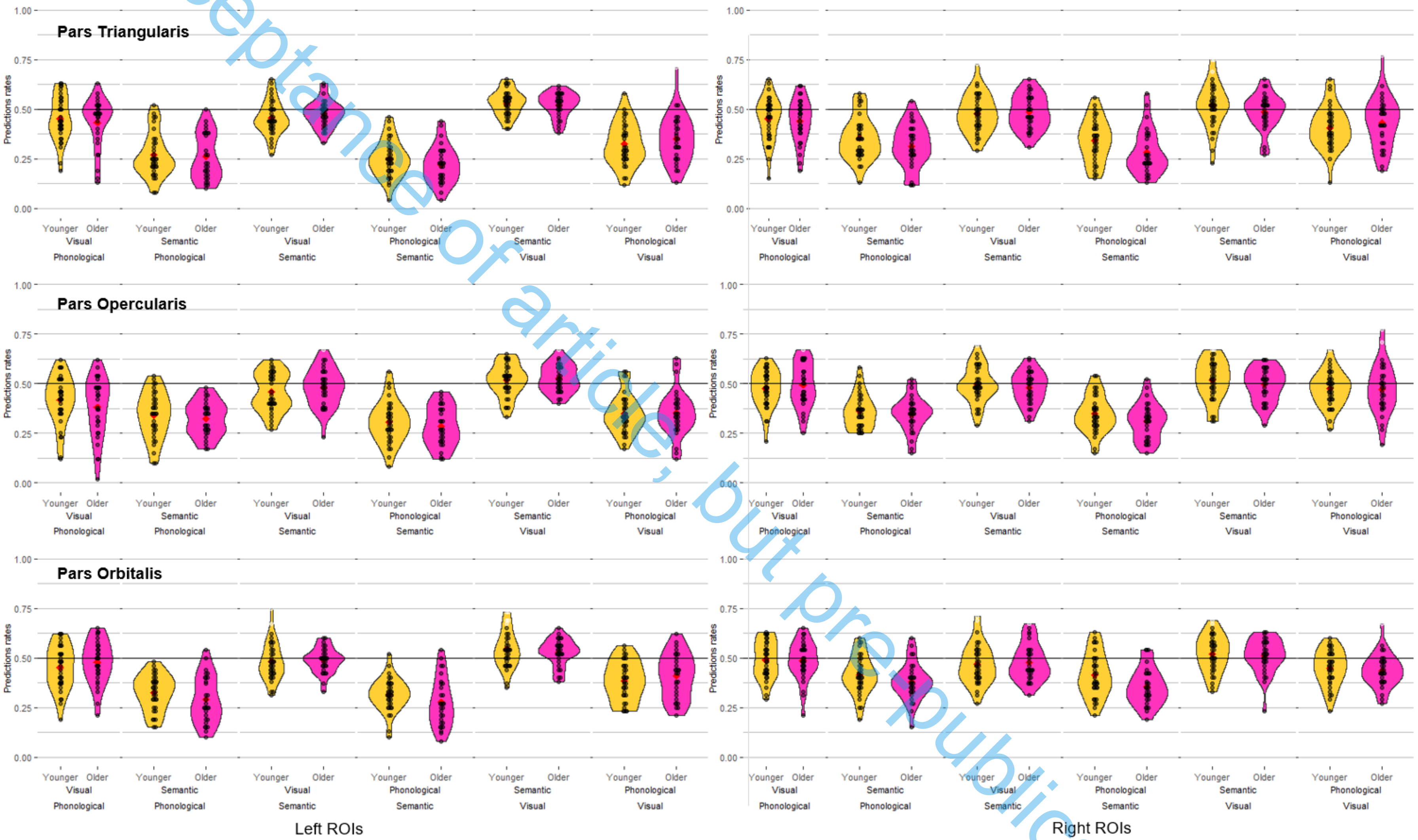
Figure 8

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%). Black dots represent the mean. Red dots represent the mean. Yellow: young adults; Pink: Older 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%). Black dots represent the mean. Yellow: young adults; Pink: Older adults.

Table 5

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

		Domain (trained → predicted)		Younger adults	Older adults
Whole-Brain				BF_{01}	
		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 older healthy participants. By using structurally equivalent similarity-judgment paradigms for measuring RI in the three domains, we observed, at the univariate neural level, a main effect of the 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 the 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 hypothesis (i.e., evidence for chance-level prediction), 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, 2006; 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 older adult populations. Interestingly, our data are also in agreement with previous studies that have highlighted the common involvement of the IFG in RI across domains (Funahashi, 2022;

Kadota et al., 2010; 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, 2017)

RI and Aging

At the behavioral level, we demonstrated that older 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, 1996). Furthermore, the group-by-condition interaction indicates that the older group was disproportionately affected by the RI condition. This is in line with previous studies that showed age-related increases in 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. Furthermore, although the general 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. Thus, the univariate age effects that were observed for only one of the analyses need to be considered with caution. The potential discrepancy between univariate and multivariate age effects could reflect that the fact that older adults demonstrate similar neural differentiation for RI, but they may need to recruit more neural resources to achieve this at the univariate level. This aligns with the concept that older adults compensate for cognitive decline by increasing the intensity of activation in existing networks or by recruiting additional neural networks (e.g., Guerrero et al., 2022, 2023; see L. Aron et al., 2022 and McDonough et al., 2022for reviews on the adaptative brain in aging). Indeed, 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; 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. In terms of task demands, the RI condition effect was stronger in the phonological domain 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 both the increased task difficulty and RI effect in the phonological task could be related to the low familiarity of the stimuli (nonwords) for the phonological task, compared to the words and basic visual features used in the other two tasks. Note that that our behavioral effects are also in line with a recent study from Chasles et al. (2024) showing that older adults were significantly less vulnerable to interference in a semantic task than in a phonological task. The lower familiarity with phonological material might lead to less stable representations of the information to be processed and compared, thereby increasing the demand for RI processes (Brainerd & Reyna, 2002; Chasles et al., 2023). One consequence of this could be that RI processes are recruited to a higher extent also in the facilitation condition, as representations will become unstable overall, leading to a reduced RI effect when contrasting the interference and facilitation conditions . Critically, this did not seem to be the case as the behavioral RI effect was increased rather than decreased in the phonological condition. Hence, despite overall lower familiarity potentially resulting in less stable representations, both conditions still significantly differed in the extent of RI involved. This situation also did not have a measurable 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. Moreover, follow-up analyses had shown that, overall, task difficulty did not appear to impact our results, as multivariate differences in classification accuracies for RI effects could not be explained by differences in task difficulty across domains. Task difficulty is therefore unlikely to have significantly affected the pattern of results we observed. We, however, need to acknowledge the increased behavioral RI effect for the phonological condition relative to the other domains, which prompts us to consider with caution the lack of prediction of neural RI effects between this domain and other domains. At the same time, note that the same lack of between-domain prediction of neural RI effects was observed for visual and semantic domains for which behavioral RI effects were of the same size.

More generally, the question addressed here mirrors similar questions in other related domains such as the domain-specificity of attentional control or attentional resources in working memory. Some evidence suggests that there are both domain-general and domain-specific working memory resources, for verbal working memory (Morey & Mall, 2012) while visual working memory may rely more exclusively on domain-general resources (Morey & Miron, 2016), with both working memory modalities competing for the domain-general resources (Saults & Cowan, 2007; Vergauwe et al., 2010). In five experiments, Morey et al. (2013) explored the asymmetric interference pattern between verbal and visual-spatial tasks. The authors observed in the first four experiments that maintaining verbal items disrupted the retention of visual-spatial items. However, there was no convincing evidence that verbal memoranda were specifically impaired by maintaining visual-spatial information. This was further confirmed by the fifth experiment in which participants' correct answers were rewarded in one WM domain or another. In 2014, Cowan and colleagues went further by conducting nine experiments in the verbal and visual domains. Based on their results, the authors concluded that items do not always remain in central, general storage; instead, they are often moved to peripheral, domain-specific, storage, when possible, except for roughly one item at a time that is kept in central attention (Cowan et al., 2014). The same nuanced findings regarding domain-specific and domain-general resources can also be observed in the neuroimaging literature of working memory. While verbal and visual working memory both recruit similar frontoparietal cortices associated with top-down attentional (e.g., Majerus et al., 2016), other studies have also shown that the neural patterns defining specific aspects of attentional control such as selection of attention differ in verbal and visual working memory tasks (Majerus et al., 2018). This is in line with the concluding remarks from Nozari and Martin (2024) stating that "*in terms of neural correlates, working memory contains both domain-general and -specific elements. Finally, in terms of application, it is mostly domain-specific*" (p.12). We must therefore remain careful when comparing the discussions about the question of domain-specificity for executive control processes such as RI vs attentional control/working memory processes. RI and attentional control likely refer to different aspects of cognitive control (e.g., Miyake et al., 2000) with each having their own levels of domain-specificity.

Conclusions

This study provides novel evidence for the domain-specificity, and, to some extent, 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 analysis techniques to allow for a full appreciation of the nature of IFG involvement in RI across different domains.

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). 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/.

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