Aging and binding in short-term memory: Processes involved in conjunctive and relational binding

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Abstract

In visual short-term binding memory tasks, some studies suggested that aging disrupts relational binding more than conjunctive binding, whereas others report equivalent age-related differences in both types of binding. Yet, demands in controlled resources are potentially the greatest for relational short-term binding. In order to test the hypothesis that aging would affect preferentially tasks demanding in controlled processes, we assessed the contribution of controlled and automatic memory processes to relational and conjunctive short-term binding. Groups of young and older adults studied shape-colour (Exp.1 and 3) or object–colour (Exp.2) pairs in a relational condition in which items were linked to colour patches and a conjunctive condition where colour was integrated into the items. Memory for bindings was tested with a reconstruction task (Exp. 1 and 2) or with a recognition memory task (Exp. 3) under inclusion and exclusion instructions (Process Dissociation Procedure). The three experiments showed that the retrieval of both relational and conjunctive bindings relied primarily on controlled memory processes, the use of which was diminished in older participants. This study brings additional evidence that age-related differences in top-down control processes explain at least partly decreased short-term binding capacities.

Keywords: aging, visual short-term binding, conjunctive binding, relational binding, process dissociation procedure.

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Introduction

Episodic memory decline in aging can be partly explained by a decreased capacity to encode and retrieve associations between pieces of information (Old & Naveh-Benjamin, 2008). However, all forms of binding may not show similar age-related differences. In particular, a distinction is made between conjunctive and relational binding. Conjunctive binding happens when features are integrated into a unified representation (i.e., intra-item or intrinsic binding, Ecker et al., 2007; Mayes et al., 2007; O'Reilly & Rudy, 2001), such as colour as an object’s feature. Relational binding refers to the associative and flexible link between independent items or between items and context or extrinsic binding (Cohen et al., 1999; Ecker et al., 2007). In long-term memory, conjunctive binding remains better preserved than relational binding in older adults (Bastin et al., 2013). One explanation for these differential age-related changes is that conjunctive and relational bindings are encoded in different brain areas and that they involve different retrieval processes, that are not affected similarly by aging. In particular, relational binding relies on the hippocampus, whereas conjunctive binding can be supported by medial temporal lobe cortices (i.e., perirhinal and entorhinal cortices) (for a review, see Bastin et al., 2019) and there are larger volume reductions of the hippocampus than of the medial temporal lobe cortices during aging (Yonelinas et al., 2007). Moreover, age-related decreased ability to retrieve relational item-colour associations have been related to decreased recollection capacities, whereas relatively intact memory for item-colour conjunctions would be supported by preserved familiarity-based retrieval processes (Bastin et al., 2013).

Considering that the same representations may support short-term and long-term memory (Baddeley, 2000; Yonelinas, 2013), several studies examined binding in visual short-term memory[[1]](#footnote-1) and also reported age differences in the ability to maintain temporarily bindings. Most frequently, evidence for age-related short-term binding difficulties was reported when tasks involved relational binding (Borg et al., 2011; Brockmole & Logie, 2013; Chen & Naveh-Benjamin, 2012; Cowan et al., 2006; Fandakova et al., 2014; Lecouvey et al., 2015; Lugtmeijer et al., 2019; Mitchell, Johnson, Raye, Mather, et al., 2000; Peich et al., 2013). Of note, the most consistent difficulty concerns extrinsic associations between items, such as shape-colour or face-scene pairs. Indeed, a few studies reported age-invariance for item-location associative short-term memory (Pertzov et al., 2015; Read et al., 2016; Rhodes et al., 2017). In contrast, age invariance in conjunctive binding in short-term memory, such as coloured shape memory, was found in most studies (Brockmole et al., 2008; Brown & Brockmole, 2010, Experiment 1; Brown et al., 2017; Forsberg et al., 2019, Experiment 2; Hoefeijzers et al., 2017; Isella et al., 2015; Killin et al., 2018; Parra et al., 2009; Rhodes et al., 2016, 2017), but not all (Brown & Brockmole, 2010, Experiment 2; Brown et al., 2017, Experiment 3; Forsberg et al., 2019, Experiments 1 and 3). However, before suggesting that the differential aging profile on conjunctive and relational binding that is seen in long-term memory is mirrored in short-term memory, direct comparison between the two types of short-term binding within a single experiment is necessary.

 The few studies that proceeded with this direct comparison yielded divergent findings, showing either equivalent age differences on both types of binding (Peterson & Naveh-Benjamin, 2016; van Geldorp et al., 2015), or no age-related associative binding deficit in neither conditions (Kirmsse et al., 2018), or differential age-related changes according to the type of binding (Bastin, 2018). In van Geldorp et al. (2015), young and older adults studied displays of 4 shape-colour pairs presented either as conjunctive bindings (i.e., coloured shape) or relational bindings (i.e., black-and-white shape attached to a coloured blob). At test, participants had to reconstruct studied pairings from a set of 5 shapes and 5 colours. The task was performed with and without a concurrent interfering task. The proportion of correctly reconstructed pairs was more affected by interference in the relational binding than the conjunctive binding condition. Critically, older adults performed equally poorly in both conditions compared to young participants, suggesting equivalent age-related differences in conjunctive and relational binding. Peterson and Naveh-Benjamin (2016) ran separate experiments to assess age-related differences in shape-colour (conjunctive) and shape-location (relational) short-term binding. In each task, participants studied displays of 3 or 4 pairings and then had to recognize studied versus new items or pairings in a single-probe recognition memory test. Moreover, the trials were completed either under full attention or under divided attention with a concurrent articulatory suppression task during encoding and maintenance. The results demonstrated the presence of an age-related associative decline for relational as well as conjunctive binding, but, for the latter, only when no concurrent task was added. However, by design, the extent of these age-related associative declines was not directly comparable.

In Bastin (2018), young and older participants studied sequentially a number (2, 3 or 4, depending on the task version) of object–colour pairings corresponding to their individual object span level in a relational task in which real-life objects were associated to colour patches and a conjunctive task where colour was integrated into the real-life object. Memory for individual items and for bindings was tested with a single-probe recognition memory test. Evidence for an age-related associative deficit was observed in the relational binding task, but not in the conjunctive binding task. Finally, Kirmsse et al. (2018) presented arrays of 3 shape-colour pairs to young and older adults, either as integrated coloured shapes or as extrinsic shape-coloured frame pairs. Encoding requested either to try and remember the bindings (“direct test”) or to try and remember the shape only (“indirect test”). Test trials consisted in a single-probe change detection task assessing either memory for bindings or memory for shapes only. In the direct test condition, no age-related associative deficit was found, neither for conjunctive nor for relational pairings. In the indirect test condition, only older adults demonstrated a cost in terms of performance and response time when they had to evaluate a different colour-shape pairing than at encoding, and only for conjunctive trials, suggesting enhanced memory for irrelevant conjunctive bindings in aging.

 In the face of inconsistent findings, there is a need for further investigation of the differential impact of age on conjunctive and relational short-term binding. One research track concerns the processes involved in these tasks. First, visual short-term memory for bindings requires the integration of features into coherent representations (Sander et al., 2012), with encoding of relational bindings being achieved in the hippocampus and encoding of conjunctive bindings occurring in the medial temporal cortices (Olson et al., 2006; Parra et al., 2013; Race et al., 2013; Yonelinas, 2013). Like for long-term memory, one could predict that older adults are better at retaining conjunctive than relational pairs in short-term memory because the latter are encoded in a brain area that is more sensitive to aging. However, a second component needs to be considered: the involvement of top-down controlled retrieval processes in visual short-term memory for bindings (Baddeley, 2000; Sander et al., 2012). Working memory is thought to involve both control of active representations and more automatic processing akin to familiarity (Engle & Kane, 2003; Oberauer, 2005). Poorer controlled processes may particularly contribute to explain age-related changes in short-term memory binding performance (Sander et al., 2012). Importantly, short-term memory for cross-domain extrinsic associations such as shape-colour pairs or face-scene pairs involved in relational binding may be more demanding in terms of domain-general attentional resources than short-term memory for conjunctive bindings (e.g., coloured shapes). Indeed, relational extrinsic binding is more disrupted by the presence of a concurrent task throughout the test trial than conjunctive binding (Allen et al., 2006, 2012; Ecker et al., 2013; Peterson et al., 2019; Peterson & Naveh-Benjamin, 2017; van Geldorp et al., 2015; Vergauwe et al., 2014), suggesting that active maintenance of associative representations of separate features may be more vital to successful performance in the former case.

 In healthy aging, prior research has suggested that memory decline could be partly explained by reduced attentional resources (Craik, 1986) and less efficient cognitive control (Zacks & Hasher, 1994). More generally, older adults appear particularly vulnerable to high demands in effortful or controlled processes when performing short-term or long-term memory tasks (Craik & Salthouse, 2008). This is notably evidenced in tasks that disentangle the contribution of conscious, explicit, controlled memory processes from that of more unconscious, automatic memory processes, such as those applying the principles of the Process Dissociation Procedure (Jacoby, 1991). In these tasks, older participants typically demonstrate decreased controlled memory processes and spared automatic memory processes both in long-term memory (Koen & Yonelinas, 2014, for a meta-analysis) and in short-term memory (Hedden & Park, 2003; Schmiedek et al., 2009). Consequently, if relational and conjunctive short-term binding require different levels of cognitive control and attentional resources and if this translates into differential reliance on controlled and automatic memory processes, one may expect differential age-related differences across tasks with larger decline in conditions that demand more controlled processes.

 There is some evidence that poorer relational binding in short-term memory as a function of age could at least partly be explained by poorer cognitive control. For instance, impaired short-term memory for object-location bindings in older adults was associated with reduced activation of prefrontal areas in a functional magnetic resonance imaging study (Mitchell, Johnson, Raye, & D'Esposito, 2000). Mitchell et al. (2000) concluded that prefrontal areas may support reflective and executive processes that would coordinate strategies to control the coactivation of components in associations and maintain them coactive, and that older individuals may experience difficulties with such reflective processes. More recently, Lecouvey et al. (2015) reported that older adults’ decreased performance in short-term memory for letter-location bindings was significantly explained by reduced processing speed and executive functioning (particularly, inhibition). Short-term binding performance of older participants correlated with metabolism in prefrontal cortex, insula and anterior and middle cingulate cortex, as measured with [18F]FDG-PET imaging. Moreover, when the contribution of inhibition and processing speed was statistically controlled for, no brain area remained correlated with performance in short-term binding. This suggests that decline in top-down controlled processes supported by prefrontal areas plays a role in explaining age-related differences in relational short-term binding. However, the degree to which controlled memory processes are involved in conjunctive versus relational short-term binding still needs to be more directly assessed.

Consequently, the current study assessed the relative contribution of controlled and automatic memory processes during retrieval in order to test the hypothesis that relational short-term binding is more sensitive to aging than conjunctive binding because it relies on controlled processes to a greater extent. We focused on item-colour bindings as the majority on previous studies in the field used this type of materials. Here, memory arrays contained the same number of features, but differed in how they were presented. Relational binding corresponded to associations in which an item and a colour are two related entities. Conjunctive binding referred to intrinsic pairings in which colour was integrated as a feature of the item. Young and older participants performed an object-colour binding task in short-term memory, under relational (i.e., colour patch attached to an object) and conjunctive (i.e., colour integrated into the object) conditions in three experiments. In Experiments 1 and 3, the object associated to the colour was a difficult-to-label shape, whereas in Experiment 2, the object was a line-drawing of a real-life object. In all experiments, in order to assess the extent to which young and older adults relied on controlled and automatic processes when remembering bindings in short-term memory, we applied the principles of the Process Dissociation Procedure -PDP (Jacoby, 1991), following on Loaiza et al. (2015) and Ste-Marie et al. (1996).

For a given memory task, the PDP relies on two conditions that only differ in terms of the instructions during the retrieval phase after some items have been studied (Jacoby, 1991). In Ste-Marie et al. (1996) and Loaiza et al. (2015), in the Inclusion condition, participants had to recall specifically the studied items; correct answers could rely on both controlled and automatic memory processes. In the Exclusion condition, the instructions required participants to produce items that were not studied from a closed set of possible answers (e.g., six-letter word starting with 3 specific letters (Ste-Marie et al., 1996); a digit between 0 and 9 (Loaiza et al., 2015)). So, producing a studied item in this condition would reflect its automatic reactivation when controlled memory processes failed. Combination of these conditions allows a quantitative estimation of the contribution of controlled and automatic processes to the task at hand. Here, the instructions were adapted to focus on memory for bindings. In the Inclusion condition, participants had to retrieve studied pairs, whereas in the Exclusion condition, they had to provide non-studied pairs among a set of possible combinations. Controlled processes would refer to conscious recollection of the actual pairing that has been studied, implying that the pairs were **consciously** maintained active throughout the trial (Engle & Kane, 2003; Oberauer, 2005). Automatic processes would be akin to familiarity and would correspond to a strength signal that reflects the degree bindings or merely their individual features (shape/colour) match previously activated representations (Oberauer, 2005). **In this view, when asked to select non-studied pairs, a participant who failed to consciously maintain active the studied pairs may select a shape-colour combination that was actually part of the study array because its recent activation made it more readily and unconsciously available than not recently activated representations.**

If relational short-term binding depends on top-down controlled processes more than conjunctive short-term binding (Allen et al., 2006, 2012; Ecker et al., 2013; Elsley & Parmentier, 2009; Peterson et al., 2019; Peterson & Naveh-Benjamin, 2017; van Geldorp et al., 2015; Vergauwe et al., 2014) and if age-related short-term memory difficulties are related to reduced attentional and controlled resources, we should observe larger age-related differences in the contribution of controlled memory processes to short-term memory of relational bindings than conjunctive bindings. The data that support the findings of this study are available at <https://osf.io/82xv4/> on the OSF open-access repository.

Experiment 1

Experiment 1 built on the paradigm used by van Geldorp et al. (2015) to compare relational versus conjunctive binding of shape-colour pairs in short-term memory in young and older adults. Instructions were manipulated in order to create inclusion and exclusion conditions that would provide estimates of the contribution of controlled and automatic processes during short-term memory trials.

Methods

*Participants*

Thirty-two young adults (age range: 19-29 years old, 16 women) and 32 older adults (age range: 65-75 years old, 16 women) participated in the study. The sample size was superior to the minimal n requested when determined a priori in order to detect a large group effect on memory performance (as in van Geldorp et al. (2015)) in a repeated-measure ANOVA with 1 between factor with a power of 0.80 at an alpha level of .05 (min. n = 22). All participants were recruited from the local community. None of them reported a neurological or a psychiatric condition that could interfere with cognitive functioning. In addition, all the older participants reported being in good health and having good hearing and vision or appropriate correction for visual or auditory disorders when necessary. No participant had colour blindness, as shown by perfect performance on the Ishihara test (Ishihara, 1917). Both groups were matched in terms of years of education (Table 1). None of the older participants demonstrated any sign of cognitive decline on a cognitive screening tool (Dementia Rating Scale (Mattis, 1973)) as their performance was within-norms (Pedraza et al., 2010). Participants gave their written informed consent to take part to the study. The study followed the principles of the Declaration of Helsinki and was approved by the Ethics Committee of the Faculty of Psychology of the University of Liège.

*Materials and procedure*

The stimuli were shape-colour pairs built from a pool of 8 shapes that were difficult to verbalize and 8 distinct colours adapted from Parra et al. (2010) and van Geldorp et al. (2015). Combinations of shapes and colours were done in such a way that all possible combinations appeared in the task at least once and no more than twice.

 Participants were tested individually. The task was computerized using Psychtoolbox and Matlab (R2015b). The procedure was inspired by van Geldorp et al. (2015). The task consisted of four blocks of 20 trials each. Each trial started with the simultaneous presentation of 4 shape-colour pairs for 4 seconds, that participants were instructed to study, followed by a blank screen for 1 second. Then, the test screen displayed 5 shapes and 5 colours. Four of each were part of the study screen, and the extra shape and colour acted as distractors to reduce the likelihood of correct answer by chance. The four blocks differed in terms of the nature of the binding (conjunctive versus relational) and of the instructions for the test phase (inclusion versus exclusion), following a 2 by 2 factorial design (see Figure 1). The order of the blocks was counterbalanced across participants. In the conjunctive binding condition, the colour was integrated into the shape. In the relational binding condition, a coloured patch was linked to the shape. Following the Process Dissociation Procedure, test instructions were either inclusive or exclusive. In the inclusion instructions, participants were asked to reconstruct the four colour-shape pairings that were studied in the trial. In the exclusion instructions, participants had to select 4 shape-colour pairings that they had not seen during the trial. Correct answers could be any combinations between the 5 shapes and the 5 colours that were different from the studied pairings. Participants responded by clicking with the computer mouse on either a colour or a shape, and then on the corresponding paired feature (i.e., shape or colour). Self-correction was allowed until the space bar was pressed to validate the trial. In each block, there were a total of 80 responses to make (20 trials x 4 pairings). Chance level corresponded to 16% (van Geldorp et al., 2015). Each block was preceded by a brief practice session involving 3 trials in order to ensure understanding of the instructions.

 Before the short-term binding task, participants were administered three tasks assessing executive functions: a 2-back task to assess updating, a Stroop task to evaluate inhibition and a Plus-Minus task to measure flexibility (Angel et al., 2016). To obtain a global executive functioning measure, we averaged z-scores (means and standard deviations of both groups) of each subtest (Angel et al., 2016), inverting the sign when necessary so that higher scores always indicated good performance. Previous work has shown that short-term memory for bindings in aging is significantly predicted by executive abilities, and especially inhibition (Lecouvey et al., 2015; van Geldorp et al., 2015). Here, we tested whether this was specifically true for the controlled processes involved in short-term binding. Finally, older participants completed the Dementia Rating Scale at the end of the session.

Statistical analyses

Performance on tests of executive function was compared between groups by means of Student T-tests. For the short-term binding task, in blocks with inclusion instructions, the score was the proportion of correctly recalled studied pairs. These scores were submitted to a 2 (Group: young, older) by 2 (Condition: conjunctive, relational) ANOVA, in which Group was a between-subject factor and Condition a within-subject factor. In blocks with exclusion instructions, the score was the proportion of reconstructed pairs that were actually studied (despite the instruction of selecting new pairings). These scores were also submitted to a 2 (Group: young, older) by 2 (Condition: conjunctive, relational) ANOVA. Following Process Dissociation Procedure equations, an estimate of the contribution of controlled processes was obtained by subtracting the score in the exclusion condition from the score in the inclusion condition, so that Controlled = Inclusion – Exclusion. This score reflects mainly the proportion of bindings that were consciously and actively maintained in short-term memory throughout the trial. The estimate of the contribution of automatic processes was obtained by the following formula: Automatic = Exclusion/(1 – Controlled). This score reflects the proportion of bindings that would yield sufficient match with previously activated representations (either of pairs or of both items) to influence memory decisions in the absence of controlled retrieval. Controlled and automatic estimates were calculated separately for the conjunctive binding and the relational binding conditions and analysed with a 2 (Group: young, older) by 2 (Condition: conjunctive, relational) ANOVA. Moreover, Pearson correlations were computed between the estimates and executive measures (composite score and individual test scores) in order to test the hypothesis that the contribution of controlled processes in short-term binding performance was associated with the participants’ executive abilities.

Often the age-related associative deficit is demonstrated by age-related differences in associative memory tests contrasting with intact item memory (Naveh-Benjamin, 2000). Here we adopted a previously used reconstruction procedure that assesses mainly associative memory to follow on work that directly compared conjunctive and relational short-term binding in aging (van Geldorp et al., 2015). Nevertheless, the reconstruction task includes some item/feature discrimination as a new shape and a new colour were included as distractors. In order to assess whether some group differences in item memory may have contributed to global reconstruction performance across conditions and groups, we estimated single feature memory by the rate of correct rejections of the distractor items in the inclusion instructions and submitted it to a 2 (Group: young, older) by 2 (Condition: conjunctive, relational) ANOVA.

For all analyses, the statistical threshold was set at p < .05.

Results

In tests assessing executive functions, older adults performed more poorly than young adults (2-back, t(62) = 3.8, p = .0003, Cohen’s d = 0.99; Stroop, t(62) = -4.2, p = .00008, d = 1.05; Plus-Minus, t(62) = -5.4, p = .000001, d = 1.37).

Performance of young and older adults in the short-term binding task as a function of condition and instructions is presented in Table 2. In the blocks with the inclusion instructions (i.e., typical recall instructions, like in Van Geldrop et al. (2015)), the 2 (Group: young, older) by 2 (Condition: conjunctive, relational) ANOVA on the proportion of correctly **reconstructed** pairs revealed a significant main effect of Group, F(1, 62) = 49.9, p < .0000001, ƞ2p = .44, indicating that young participants **reconstructed** more studied shape-colour pairs than older adults. The main effect of Condition, F(1, 62) = 0.01, p = .92, ƞ2p = .0001, and the interaction, F(1, 62) = 0.18, p = .66, ƞ2p = .002, were not significant. In the blocks with the exclusion instructions, the Group by Condition ANOVA on the proportion of studied pairs that were erroneously reconstructed revealed a main effect of Group, F(1, 62) = 28.25, p = .000002, ƞ2p = .31. Older adults selected more often studied shape-colour pairs than young adults when asked to construct novel pairings. There were no main effect of Condition, F(1, 62) = 0.84, p = .33, ƞ2p = .01, nor interaction, F(1, 62) = 0.66, p = .41, ƞ2p = .01.

Estimates of controlled processes were submitted to a 2 (Group: young, older) by 2 (Condition: conjunctive, relational) ANOVA. The analysis revealed that older adults used less controlled processes than young adults when remembering short-term memory bindings, as indicated by the main effect of Group, F(1, 62) = 67.4, p < .0000001, ƞ2p = .52. Neither the effect of Condition, F(1, 62) = 0.34, p = .55, ƞ2p = .005, nor the interaction, F(1, 62) = 0.005, p = .94, ƞ2p < .0001, were significant. The ANOVA on estimates of automatic processes indicated that older adults used more automatic processes than young adults, F(1, 62) = 10.17, p = .002, ƞ2p = 0.14. There were no main effect of Condition, F(1, 62) = 0.42, p = .51, ƞ2p = .006, and no interaction, F(1, 62) = 0.65, p = .42, ƞ2p = .01.

The ANOVA on the rate of correct rejections of the distractor items in the inclusion instructions indicated that young participants (M = .42) correctly rejected more shape and colour distractors than older participants (M = .30), F(1, 62) = 20.92, p = .00002, ƞ2p = .25. However, this estimate of item memory did not differ between conditions, F(1, 62) = 1.23, p = .27, ƞ2p = .01, and there was no Group by Condition interaction, F(1, 62) = .009, p = .92, ƞ2p = .0001. Of note, when including correct rejections of distractors averaged across conditions in the ANOVAs looking for Group and Condition effect on estimates of controlled and automatic processes, the same results as mentioned above were observed.

 Finally, in older adults, Pearson correlations between controlled/automatic estimates and the executive composite score showed that better executive functioning was associated with more use of controlled processes in the relational binding condition (r = .41, p = .01). Other scores did not significantly correlate with executive functioning (controlled processes in the conjunctive binding condition: r = .24, p = .17; automatic processes in the relational binding condition, r = -.16, p = .37; automatic processes in the conjunctive binding condition, r = -.07, p = .67). In young adults, there were two significant correlations: participants with better executive abilities had higher controlled processes estimates (r = .41, p = .01) and lower automatic processes estimates (r = -.45, p = .008) in the relational condition.

We also computed Pearson correlations between controlled/automatic estimates and individual executive scores. None of the correlations was significant in the older group. In young participants, there was a significant correlation between controlled estimates in the relational condition and n-back score (r = .44, p = .01), indicating more active maintenance of relational bindings in participants with better updating abilities. There was also a significant correlation between automatic estimates in the relational condition and performance in the Plus-Minus (r = .47, p = .006), showing that participants with poorer flexibility (i.e., the score reflects the cost due to switching) relied more on automatic processes in the relational condition.

Discussion

Experiment 1 indicated that age-related differences in short-term binding performance was driven by a decreased use of controlled memory processes which contrasted with a greater reliance on automatic memory processes in the older group. This aligns with the findings of a specific reduction of controlled memory processes in older adults in long-term memory (Koen & Yonelinas, 2014) and in short-term memory (Hedden & Park, 2003; Schmiedek et al., 2009) and extends it to the domain of short-term maintenance of bindings. Of note, this reconstruction task appeared to rely mostly on the contribution of controlled processes, as automatic estimates were close to chance. With regard to differences related to the nature of the bindings (relational versus conjunctive), Experiment 1 did not provide any support to the idea that relational binding is more demanding in controlled and active maintenance of bindings in memory and would be more impacted by aging than conjunctive binding. In contrast, there was no main effect of the condition on the estimates of automatic and controlled processes, and no significant group by condition interaction.

Nevertheless, the extent to which older individuals relied on controlled processes in the relational condition was related to their executive abilities, indexed by a composite score combining measures of updating, inhibition and switching, but not to a specific executive function. Similarly, variability in the relative contribution of controlled and automatic processes in the relational condition in young participants was related to variability in executive abilities (globally, and more specifically in updating and switching). The correlation in older participants is in line with past research suggesting a critical role played by altered top-down control processes, here referring to executive functioning, in age-related differences in short-term binding (Sander et al., 2012), especially for relational binding. Consistently, van Geldorp et al. (2015) showed that a significant part of variance in binding performance in older adults was explained by a composite score of executive functioning tests, whereas adding a measure of spatial memory, thought to reflect hippocampal involvement, did not predict short-term binding scores. Lecouvey et al. (2015) also reported that relational short-term binding in older adults was partly explained by individual’s executive abilities (especially inhibition skills), as well as processing speed. They further showed that individual differences in prefrontal and anterior cingulate metabolism were related to individual variations in binding scores, and that such relationship was no longer significant when statistically controlling for inhibition and processing speed scores.

The lack of interaction between age and condition differs from our previous study showing better performance for conjunctive short-term binding than for relational short-term binding (Bastin, 2018). In that study, stimuli were line-drawings of real-life objects in contrast to most studies that used geometrical shapes. Although Brockmole and Logie (2013) did not find any difference in performance across age as a function of the use of shapes versus drawings of animals, the use of familiar objects may activate long-term representations in semantic memory, which may facilitate reliance on automatic strength signals (Oberauer, 2005). Given that older adults prioritize semantic information over memory for details (Umanath & Marsh, 2014), including in working memory (Hoefeijzers et al., 2017; Loaiza & Srokova, 2019), the finding of an age-related advantage for conjunctive binding in Bastin (2018) may have been due to the promotion of such activation of semantic representations. Experiment 2 thus aimed at replicating Experiment 1 by replacing shapes by line-drawings of real-life objects.

Experiment 2

Experiment 2 again assessed the hypothesis of larger age-related differences in the contribution of controlled memory processes to short-term memory of relational bindings than conjunctive bindings, by using the Process Dissociation procedure in a task involving real-life object-colour pairs. If the hypothesis were supported here, while it was not in Experiment 1, this might indicate that the nature of the materials matters and that conjunctive bindings for pre-experimentally familiar stimuli may facilitate reliance on automatic assessment of memory strength, which would be particularly beneficial to older participants whose controlled processes are less efficient.

Methods

*Participants*

Twenty young adults (age range: 18-28 years old, 10 women) and 20 older adults (age range: 60-74 years old, 12 women) from the local community participated in the study. They had no neurological or psychiatric condition that could interfere with cognitive functioning. All the older participants reported being in good health and having good hearing and vision or appropriate correction for visual or auditory disorders when necessary. No participant had colour blindness, as shown by perfect performance on the Ishihara test (Ishihara, 1917). Both groups were matched in terms of years of education (Table 3). All older participants performed within norms on the Dementia Rating Scale (Mattis, 1973; Pedraza et al., 2010). Participants gave their informed consent to take part to the study. The study was approved by the Ethics Committee of the Faculty of Psychology of the University of Liège.

*Materials and procedure*

The procedure was similar to that in Experiment 1, with two exceptions. First, shapes were replaced by pictures of objects from the database of Bonin et al. (2003). Eight objects form the pool of pictures: a calendar, a canoe, an ink pad, an iced choco, a sailing ship, a bucket, a binder, and a wrapped present. Objects were chosen so that they had no prototypical colour and their pairings with colours were unfamiliar. Second, as the objects were nameable, verbalization was prevented by asking participants to repeat “1-2-3-4” during study and delay. This ensured that we measured visual short-term memory and avoided an influence of verbal short-term memory (Brockmole et al., 2008; Brown et al., 2017; Forsberg et al., 2019; Rhodes et al., 2016), but still allowed the possible influence of activated visual representations of semantically-related exemplars. Figure 2 illustrates the 2 (Condition: conjunctive, relational) by 2 (Instructions: inclusion, exclusion) design of the task.

Results

Two (Group: young, older) by 2 (Condition: conjunctive, relational) ANOVAs were conducted on the proportion of correctly **reconstructed** pairs in the inclusion instructions, on the proportion of studied pairs that were erroneously reconstructed in the exclusion instructions, as well as on estimates of controlled and automatic processes. Scores are presented in Table 4. The statistical threshold was set at p < .05.

 In the blocks of the inclusion instructions, the ANOVA revealed a main effect of Group, F(1, 38) = 32.2, p = .000002, ƞ2p = .45, showing that young adults performed better than older adults in the **reconstruction** of studied object-colour pairs. The main effect of Condition did not reach significance but was of medium size, F(1, 38) = 3.7, p = .06, ƞ2p = .08, suggesting slightly better performance in the conjunctive binding than in the relational binding condition. The interaction was not significant, F(1, 38) = 1.6, p = .20, ƞ2p = .04. In the blocks with the exclusion instructions, the analyses showed no main effect of Group, F(1, 38) = 0.45, p = .50, ƞ2p = .01 and no interaction, F(1, 38) = 1.7, p = .19, ƞ2p = .04. The main effect of Condition did not reach significance, but was a medium size, F(1, 38) = 3.1, p = .08, ƞ2p = .07, indicating that participants endorsed more unstudied pairs in the relational than the conjunctive condition.

 The ANOVA on controlled processes yielded a significant main effect of Group, F(1, 38) = 21.5, p = .00004, ƞ2p = .36. This was due to poorer estimates of controlled processes in older adults than in young adults. The main effect of Condition was also significant, F(1, 38) = 5.8, p = .02, ƞ2p = .13, showing that controlled processes were used more in the conjunctive than in the relational binding condition. The Group by Condition interaction was not significant, F(1, 38) = 0.17, p = .67, ƞ2p = .004.

 The analyses of estimates of automatic processes showed a main effect of Group, F(1, 38) = 4.2, p = .04, ƞ2p = .09, indicating that young adults used more automatic processes than older adults. The main effect of Condition was not significant, F(1, 38) = 0.7, p = .40, ƞ2p = .01. Although the interaction did not reach significance, it was of medium size, F(1, 38) = 3.1, p = .08, ƞ2p = .07. Post-hoc Tukey tests indicated that this marginally significant interaction was due to larger estimates of automatic memory processes in young than in older adults in the relational condition (p = .04), while there was no age-related differences in the conjunctive condition (p = .92).

The ANOVA on the rate of correct rejections of the distractor items in the inclusion instructions indicated that young participants correctly rejected more shape and colour distractors than older participants, F(1, 37) = 15.76, p = .0003, ƞ2p = .29. This estimate of item memory did not differ between conditions, F(1, 37) = 1.69, p = .20, ƞ2p = .04, but there was a significant Group by Condition interaction, F(1, 37) = 4.45, p = .04, ƞ2p = .10, which indicated that older participants rejected less distractors than young participants only in the conjunctive condition (p = .0003). Of note, when including correct rejections of distractors in the conjunctive condition in the ANOVAs looking for Group and Condition effect on estimates of controlled and automatic processes, some outcomes were different. For controlled processes, the effect of Condition was no longer significant (p = .24). For automatic processes, no effect was significant (ps > .16).

Discussion

Like in Experiment 1, the results from this Experiment indicated that age group differences were mainly driven by age-related decline in controlled memory processes during reconstruction of bindings in short-term memory trials. Age-related differences in the use of controlled processes were similarly observed in the relational and conjunctive binding condition, contrary to our hypothesis. Here, in contrast with Experiment 1, the older group also showed a mild decrease in automatic memory processes, which occurred only in the relational binding condition. Moreover, for both age groups, there was a differential involvement of controlled memory processes as a function of the type of binding, but it was conjunctive bindings that engaged more controlled processes than relational bindings, while it was not the case in Experiment 1. This finding may be due to two particularities of the task that distinguish it from the task in Experiment 1. First, contrary to our suggestion that the pre-experimental familiarity of stimuli could enhance strength signals from activated long-term semantic representations, it may be that the use of real-life objects led to the comparison of coloured objects with prior knowledge about these objects, creating some extra-associations that facilitated the active maintenance and recollection of studied pairings. This may have partly relied on stronger item memory, as this Condition effect was no longer significant when we controlled for an estimate of correct rejection of novel features. In long-term memory, materials that are consistent with pre-experimental knowledge appear to improve recollection of those materials during a recognition memory task (Bird et al., 2011; Long & Prat, 2002). Second, articulatory suppression was added throughout the encoding and maintenance phases, thus reducing the availability of general resources to keep information in the focus of attention. The fact that this particularly affected the use of controlled processes to maintain relational bindings by comparison to conjunctive bindings echoes with previous findings suggesting that relational short-term binding is more affected by the presence of a concurrent task than conjunctive short-term binding (Allen et al., 2006, 2012; Ecker et al., 2013; Elsley & Parmentier, 2009; Peterson et al., 2019; Peterson & Naveh-Benjamin, 2017; van Geldorp et al., 2015; Vergauwe et al., 2014). This had no disproportionate detrimental effects for older participants though, contrary to the initial hypothesis.

 The reconstruction task used in this Experiment and the previous one is akin to a recall task. Recall is supposed to rely more extensively on self-initiated and controlled retrieval mechanisms than recognition memory tasks (Craik, 1986). So, there may be little room for automatic processes to support a significant part of performance in the current tasks. Moreover, in the reconstruction test of both conditions, the shapes and colours were aligned as separate items in the display. This means that the perceptual arrangement of test stimuli was more similar to the perceptual arrangement of the stimuli encoded in the relational condition (separate items only related with a line) than in the conjunctive condition (colour and shape/object were fused). Given that perceptual match between study and test facilitates the reinstatement of memory representations during retrieval (Tulving & Thomson, 1973), notably the use of fluency heuristic for familiarity judgments (Westerman et al., 2002), the conjunctive condition may have been disadvantaged compared to the relational condition. Participants may have had rely on more controlled processes than they would have done, had the stimuli been visually matched between study and test. Therefore, Experiment 3 replaced the reconstruction task by a forced-choice recognition task in which test probes had the same perceptual format between study and test. Such procedure may allow participants to successfully discriminate studied and unstudied pairs using more automatic memory processes (Bastin & Van der Linden, 2003).

Experiment 3

The relative contribution of controlled and automatic memory processes, as indexed by the PDP, to the short-term memory of relational and conjunctive bindings and their interaction with aging was again assessed. The procedure of Experiment 1 was used, but the test phase involved a recognition memory task instead of a reconstruction task.

Methods

*Participants*

Twenty-four young adults (age range: 18-30 years old, 12 women) and 24 older adults (age range: 65-81 years old, 12 women) from the local community participated in the study. None of the participants had any neurological or psychiatric condition that could interfere with cognitive functioning. Participants reported being in good health and having good hearing and vision or appropriate correction for visual or auditory disorders when necessary. None had colour blindness, as shown by perfect performance on the Ishihara test (Ishihara, 1917). One young participant was excluded from the analyses because of a failure to comply with instructions in the exclusion condition. Both groups were matched in terms of years of education (Table 5). All older participants performed above the cut-off score of 26/30 on the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005). Participants gave their written informed consent to take part to the study. The study was approved by the Ethics Committee of the Faculty of Psychology of the University of Liège.

*Materials and procedure*

The procedure was similar to that in Experiment 1, including 4 blocks of 20 trials involving colour-shape pairs, with one exception. Instead of a reconstruction test, the test screen presented the 4 studied pairs mixed with 4 recombined pairs (i.e., rearranging the links between colours and shapes in unstudied pairings) (see Figure 3). During this recognition memory test, participants had to click on the 4 pairs they have seen previously in the trial in the inclusion instructions, and on 4 novel pairs in the exclusion instructions. Chance level was 50%.

Results

Two (Group: young, older) by 2 (Condition: conjunctive, relational) ANOVAs were conducted on the proportion of correctly recognized pairs in the inclusion instructions, on the proportion of incorrectly endorsed studied pairs in the exclusion instructions, as well as on estimates of controlled and automatic processes. Scores are presented in Table 6. The statistical threshold was set at p < .05.

 In the blocks of the inclusion instructions, the ANOVA showed a main effect of Group, F(1, 45) = 19.1, p = .00007, ƞ2p = .29, showing that young adults recognized correctly more studied shape-colour pairs than older adults. The main effect of Condition, F(1, 45) = 0.2, p = .59, ƞ2p = .006, and the interaction, F(1, 45) = 1.2, p = .27, ƞ2p = .02, were not significant. In the blocks with the exclusion instructions, the analyses indicated that there was a main effect of Group, F(1, 45) = 28.5, p = .000003, ƞ2p = .38, due to more incorrectly endorsed studied pairs in older than in young participants. There was also a main effect of Condition, F(1, 45) = 4.8, p = .03, ƞ2p = .09, with more incorrectly endorsed studied pairs in the relational than in the conjunctive condition. Finally, there was no interaction, F(1, 45) = 0.01, p = .93, ƞ2p = .0001.

 The ANOVA on controlled processes revealed a significant main effect of Group, F(1, 45) = 29.5, p = .000002, ƞ2p = .39. Estimates of controlled processes were higher in young than in older adults. There was a marginal medium-size main effect of Condition, F(1, 45) = 3.3, p = .07, ƞ2p = .06, due to slightly more controlled processes in the conjunctive than in the relational condition. There was no significant Group by Condition interaction, F(1, 45) = 0.2, p = .62, ƞ2p = .005.

 Finally, the analyses of estimates of automatic processes did not show any significant effect: Group, F(1, 45) = 0.6, p = .42, Condition, F(1, 45) = 1.4, p = .23, Group by Condition interaction, F(1, 45) = 0.0, p = .99.

Discussion

Despite the use of a recognition memory procedure, young participants relied mainly on controlled memory processes to remember previously studied shape-colour pairs. They did so significantly more often than older adults, leading to large age-related differences in controlled-based short-term memory for bindings. Like in Experiment 2, the use of controlled processes was slightly decreased in the relational condition compared to the conjunctive condition. This was mostly due to more endorsement of studied pairs in the relational than the conjunctive condition under exclusion instructions. Why would this occur in this experiment that did not include any articulatory suppression and used shape-colour pairs as Experiment 1? The two main differences between Experiment 1 and 3 are the format of the test and the degree of visual match between study and test. Contrary to our prediction that these factors should increase the use of automatic processes that had little room to express in previous experiments, they rather affected the efficiency of controlled processes, with a particular benefit for conjunctive binding. With regard to the exclusion instructions, the range of possible correct answers was reduced here (as the array contained 4 unstudied pairs) compared to the two previous experiments (allowing the selection of several unstudied combinations). It is not clear whether this could have contributed to the above mentioned differential results, but this had an effect on global performance, which was higher in this Experiment than in the others. In other words, the task was globally easier in the current Experiment. So, in this task that was comparatively easier and less demanding than the tasks in the previous Experiments, participants had slightly more control over memory decisions in the conjunctive condition.

Finally, despite these small differences between conditions in the use of controlled processes, no interaction between group and condition was found. These findings, like in Experiments 1 and 2, did not support the hypothesis that relational short-term binding would be more associated with age-related decline in the use of controlled memory processes than conjunctive short-term binding.

General discussion

The current study aimed at assessing the relative contribution of controlled and automatic memory processes to short-term memory for bindings as a function of age group and of the nature of the to-be-remembered pairings. The Process Dissociation Procedure was used to test the hypothesis that relational short-term binding may require more controlled processes than conjunctive short-term binding. Across three experiments, the main findings were twofold: age-related decline in the ability to remember bindings in short-term memory was mainly due to reduced use of controlled memory processes, and age-related differences was mostly similar in relational and conjunctive short-term binding with no indication that older participants would struggle more in the relational than the conjunctive condition due to poor controlled processes.

 In long-term memory, the age-related associative deficit is modulated by the kind of associations that need to be encoded and retrieved. In particular, older adults have greater difficulty to remember between-domain or relational bindings than within-domain or conjunctive bindings (Bastin et al., 2013; Old & Naveh-Benjamin, 2008; Troyer et al., 2011). For instance, in a study in which young and older adults had to remember the colour paired with an object after having encoded the colour as an integrated feature of the object (i.e., conjunctive) versus as a contextual detail (i.e., relational), older adults showed relatively intact memory for conjunctive item-colour pairs, in contrast to relational associations. Moreover, memory for conjunctive binding in older participants was mainly supported by familiarity (Bastin et al., 2013). This is in line with current memory models that suggest that the hippocampus –which is affected during aging- support the encoding and recollection of complex relational bindings, whereas adjacent rhinal cortices –which remain preserved in aging- encode object-level representations, including intra-item or conjunctive binding, and support their recognition with familiarity (Bastin et al., 2019; Montaldi & Mayes, 2010; Ranganath & Ritchey, 2012; Yonelinas, 2013). Considering that the representations that are created and stored in the hippocampus and rhinal cortices not only support long-term memory, but also other tasks like short-term memory or perceptual discrimination, some models predict that changes to the integrity of the hippocampus or rhinal cortices will have the same consequences across a variety of tasks, notably long-term and short-term memory tests for associations (Bastin et al., 2019; Yonelinas, 2013). However, the findings from the current study do not support this hypothesis of a differential age-related difference in relational versus conjunctive short-term binding, that would mimic that observed in long-term memory, in which a greater reliance on automatic memory processes such as familiarity would favour memory for conjunctions.

 This lack of a parallel between findings in short-term and long-term memory could be explained by methodological differences between long-term and short-term memory studies. Indeed, paradigms differ in many respects, such as the length of the retention interval, the nature of the stimuli (more complex and meaningful in long-term memory paradigms than in short-term memory paradigms) and the cycle of study-test phases (i.e., study and test phases are separated, and include very few cycles if any in long-term memory paradigms, whereas many cycles succeed in short-term memory task) (Chen & Naveh-Benjamin, 2012). One additional difference would be the fact that component stimuli typically repeat across short-term memory trials (e.g., shape-colour pairs are created from a limited pool of shapes and colours) whereas stimuli are more often unique in long-term memory trials. The characteristics of the short-term memory tasks make them strongly reliant on attentional and controlled processes, in addition to the use of specific representations (Baddeley, 2000; Sander et al., 2012). In the current experiments, performance appeared to rely to a large extent on controlled memory processes, which were diminished in older participants. So, age-related differences in short-memory for bindings in the current study probably reflected changes in the implementation of top-down control mechanisms, rather than changes in the underlying representations, as suggested by the correlation between controlled memory processes and executive abilities in Experiment 1.

 With some exceptions that will be discussed below, controlled memory processes appeared to contribute relatively similarly to relational and conjunctive short-term binding and no group by condition interaction emerged. This may appear surprising given previous findings suggesting that relational binding is more demanding in terms of domain-general attentional resources than conjunctive binding (Allen et al., 2006, 2012; Ecker et al., 2013; Elsley & Parmentier, 2009; Peterson et al., 2019; Peterson & Naveh-Benjamin, 2017; van Geldorp et al., 2015; Vergauwe et al., 2014). Of note, these studies mainly focused on the division of attention during the short-term memory trials, reporting greater disruption by the presence of a concurrent task when the associations are relational in nature compared to integrated shape-colour pairings. Here, our focus was rather on the use of specific retrieval processes that would allow to maintain active the specific bindings presented during the study display. These controlled processes would contrast with selection of studied pairs based on **an** **unconscious strength signal** either for the items or for their pairing or also on lucky guessing when the participant forgot the studied pairs. Across the three Experiments, it appeared that reliance on controlled retrieval processes dominated in both the conjunctive and relational conditions and were diminished in older adults, as suggested by the consistent age differences in inclusion conditions across all three experiments. In contrast, automatic processes were either spared in older participants (Exp. 1 and 3) or diminished (Exp. 2).

We should first consider these observations in the face of the methodological differences between the three experiments. First, Experiment 1 and 2 used a reconstruction task, while Experiment 3 used a forced-choice recognition memory task. Demands in top-down control processes were high in the reconstruction task which is similar to a recall task. Moreover, the use of automatic processes that might have supported retrieval of conjunctive bindings was hindered by the important perceptual mismatch between study and test trials in this condition. Also, item memory contributed to performance, as some unstudied features were present in the test display. With regard to this point, although older adults were less accurate in rejecting unstudied features, poor item memory did not affect differentially short-memory for bindings in the two conditions. But item memory played some role in the greater use of controlled processes in Experiment 2, possibly because of the support of pre-existing knowledge about objects. In contrast, Experiment 3 resolved all these issues by proposing perceptually-matched study and test probes in a recognition paradigm supposed to facilitate familiarity-based retrieval, with no involvement of item memory. Two results were different between Experiments 1/2 and Experiment 3. In Experiment 3, there was an effect of Condition with exclusion instructions: both groups made more commission errors in the relational than in the conjunctive condition. The same effect appeared in Experiment 2, but was only marginally significant. This may indicate that the task characteristics (such as the study-test perceptual match) were more favourable to the conjunctive condition in Experiment 3 by decreasing the odds of recollection failure. For automatic processes estimates, Experiment 3 did not reveal any group difference, in contrast to a greater reliance in the older group in Experiment 1 and in the young group in Experiment 2. The forced-choice format may have promoted equivalent contribution of familiarity-based decisions in both groups (Delhaye & Bastin, 2018). **Of note however automatic estimates were often close to chance levels (see below).**

Second, Experiments 1 and 2 have identical methodologies with two exceptions: the nature of the materials (difficult to name shapes versus pictures of real-world objects) and the presence of articulatory suppression (only with nameable objects). When using objects and articulatory suppression, conscious and active maintenance was higher for conjunctive bindings than for relational bindings. The meaningfulness of the coloured objects may have provided more elaborate encoding, and thus better maintenance, than less meaningful colour patches linked to an object (Bird et al., 2011; Long & Prat, 2002). Moreover, divided attention typically hampers the maintenance of relational bindings more than that of conjunctive bindings (Allen et al., 2006, 2012; Ecker et al., 2013; Elsley & Parmentier, 2009; Peterson et al., 2019; Peterson & Naveh-Benjamin, 2017; van Geldorp et al., 2015; Vergauwe et al., 2014). Here, this applied specifically to the estimates of controlled memory processes and expressed as increased errors in the exclusion instructions, in line with a study showing that articulatory suppression diminish control during exclusion trials in a sequence generation task (Gaillard et al., 2012). Nevertheless, this difference between conditions and the fact that controlled processes were diminished in older adults were not sufficient to create a differential age-effect for short-term relational binding. However, the marginal interaction between group and condition for automatic processes estimates could suggest that young adults managed to compensate the greater difficulty to actively maintain relational representations by relying on strengths signals more than older adults.

Beyond methodological differences, the Experiments had some similarities that may have favoured the predominant reliance on controlled retrieval processes in both the conjunctive and the relational condition, making them vulnerable to aging despite subtle differences between conditions. First, it has been suggested that, even if conjunctive binding may require less attentional demands than relational binding in short-term memory, the maintenance of bindings in general may be fragile, vulnerable to interference and easily overwritten by competing or subsequent information (Allen et al., 2013; Oberauer et al., 2016). For instance, the short-term maintenance of shape-colour bindings is disrupted by subsequent presentation of a to-be-ignored stimulus (Che et al., 2019; Ueno et al., 2011). Importantly, Brown et al. (2017, Experiment 3) showed that older adults are more susceptible to interference during short-term memory for shape-colour pairs and this affects memory for single features as well as bindings.

 It may be that the tasks used in the current experiments necessitated a mobilization of top-down control resources in both conditions to resist interference because test trials requested that participants retrieved all studied pairs among a display including many possible combinations of features. Indeed, the need for top-down control processes to overcome interference seem to be more prominent in **trials with multiple test probes** than single-probe trials. For instance, Wheeler and Treisman (2002) showed that memory for bindings is poorer than memory for single features when tested with a test trial including all test probes in a change detection task, whereas short-term memory for bindings equals memory for single features when the test trial assesses only one item (single-probe display). **When multiple test probes must be processed**, sufficient resources must be allocated to the maintenance of all original bindings, so that their connections do not disintegrate when confronted with new possible bindings (Allen et al., 2006). In contrast, single probe test facilitates the maintenance of original bindings, as no alternative pairs compete during test. Of note, both relational and conjunctive bindings would be vulnerable to interference in **multiple-probe displays** (Wheeler & Treisman, 2002). So, **the need to select several pairs in the current reconstruction and recognition memory tests** may at least partly explain the important contribution of controlled memory processes in relational and conjunctive binding conditions here. Indeed, the likelihood of interference and forgetting was higher in this type of paradigm than in tasks where only one pairing must be assessed. Future work should assess whether a greater reliance on controlled processes for relational short-term binding than for conjunctive short-term binding emerges when using a single-probe recognition memory test.

 A second commonality across Experiments is the possibility to implement retrieval strategies as a direct consequence of the fact that all pairings had to be retrieved **during test trials**. The successive selection among the display left room for educated guesses. For instance, in the reconstruction tasks, if a participant recollected one pair, knew that one colour was not studied, could tell that a given colour was not with a given shape, and took into account that no shape and colour was repeated with study displays, s/he could combine all this knowledge to strategically identify shape-colour combinations that were likely to be together. Similarly, in the forced-choice recognition task, when a participant knew for sure that shape A and colour X were together, they could deduce that any other test stimuli including one of these features had to be recombined unstudied pairs. These inferential strategies would apply similarly to the conjunctive and relational conditions and may have contributed to controlled memory estimates.

 **It should be noted that the current application of the PDP to short-term binding memory has not been validated. In particular, we assumed that exclusion trials would provide opportunities for an automatic and unconscious strength signal matching the probe with recently activated representations to express (Oberauer, 2005). However, an alternative view could be that participants selected erroneously the studied pairs because they completely forgot about them. If so, automatic influence on performance was not appropriately captured. Comparison of automatic estimates with base rates (i.e., chance levels) suggests that this might have been partially the case. In Experiment 1, automatic estimates did not significantly differ from chance (one-tailed t-tests, ps > .13). In Experiment 2, automatic estimates were all significantly superior to chance (ps < .013). It might be that articulatory suppression and/or use of real-life objects were a facilitator factor for observing automatic influences in short-term binding. In Experiment 3, automatic estimates significantly differ from chance only in the conjunctive condition in older adults (p = .008). What would be the take-home message of the current study if one considers that the PDP was not efficient at isolating automatic influences on performance? With the current reconstruction and recognition tasks, older adults were consistently poorer at actively maintaining and remembering the studied bindings than young adults, and this was equally evident for relational and conjunctive bindings. This suggests that the age-invariance in conjunctive bindings observed in previous studies is not universal.**

 **Moreover,** the current findings might be specific to the type of bindings that were included in this study, namely extrinsic relational bindings of shape/object and colour and intrinsic conjunctions of shape/object and colour. The current study provides further exploration of issues raised in previous studies using mainly item-colour bindings as stimuli. However, it remains to be assessed whether other types of bindings, especially item-location bindings which are incidentally created (Campo et al., 2010; Jiang et al., 2000) or extrinsic colour-shape stimuli in which colour is the background frame of the shape (Ecker et al., 2013), would be affected similarly by age-related reduction of control processes. **In study displays as the ones used here as well as in other similar studies, memory load could be higher in the relational than the conjunctive condition. Because of the automatic encoding of location together with the item (Olson & Marshuetz, 2005), more localised information needs to be processed when items linked to coloured blobs are shown compared to when colour is integrated in the items. Here, age-related differences in retrieving studied pairs were not much influenced by the nature of bindings, suggesting that such encoding load differences did not create a disadvantage for relational binding in aging.** Another point to mention is that presentation time (4 sec per array) was longer than in many previous working memory experiments (Brockmole et al., 2008; Brown & Brockmole, 2010; Cowan et al., 2006; Fandakova et al., 2014; Parra et al., 2009; Peich et al., 2013; Peterson & Naveh-Benjamin, 2016; Read et al., 2016; Rhodes et al., 2017), but still within the range of several other studies that form the background of the current work (Brockmole & Logie, 2013; Chen & Naveh-Benjamin, 2012; Hoefeijzers et al., 2017; Isella et al., 2015; Lecouvey et al., 2015; Pertzov et al., 2015; van Geldorp et al., 2015). Two studies indicated that the duration of presentation time (900 ms versus 1.5 or 2.5 sec) did not influence age-related changes in short-term binding (Brown et al., 2017; Rhodes et al., 2016). **Nevertheless, this long duration might have allowed some rehearsal to take place, so that the task is not entirely measuring pure short-term memory storage (Cowan, 2001).** Finally, a limitation is that, even if stimuli in Experiment 1 and 3 are deemed hard to verbally label, it is not impossible to do so. Adding articulatory suppression would have controlled for this possibility and should be done in future studies.

 In summary, the current study showed that relational and conjunctive short-term binding both relies largely on top-down controlled memory processes and were similarly sensitive to aging. According to the two-component model of binding in short-term memory (Sander et al., 2012), there are age-related changes in the integration of features into coherent representations associated with the integrity of the medial temporal lobe, as well as in top-down control mechanisms supported by prefrontal areas that coordinate the processing of bound representations. **In the current experiments, several variables converged to create tasks that were highly demanding in control processes, so that any potential differences due to the nature of the pairs were overwhelmed. Indeed, high control was required by the need to reconstruct or recognise all studied pairs during each test trial, leading to interference between possible answers, a necessity to maintain active all 4 pairs during the selection, and possible implementation of strategies.** In the current tasks, age-related changes to top-down control processes may have outweighed those in the integration of features into coherent representations.

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Declaration of interest statement

The authors report no conflict of interest.

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Table 1. Characteristics of the groups in Experiment 1

|  |  |  |
| --- | --- | --- |
|  | Young adults | Older adults |
| Age | 24.0 (2.8) | 68.9 (3.4) |
| Years of education | 13.4 (1.6) | 12.2 (3.3) |
| Gender (F/M) | 16/16 | 16/16 |
| DRSa | - | 135.9 (3.8) |
| 2-backb | 24.6 (1.5) | 23.0 (1.7) |
| Stroopc | .23 (.04) | .29 (.07) |
| Plus-Minusd | 26.0 (12.1) | 51.5 (23.3) |
| Executive composite score | .48 (.52) | -.48 (.55) |

Note. a Dementia Rating Scale (total score). b number of correct responses. C Interference score calculated as (time of Interference - time of Naming)/(time of Interference + time of Naming). d score calcutated as (time in alternation) – (time in addition + time in subtraction)/2

Table 2. Experiment 1: Short-term binding performance as a function of group and condition

|  |  |  |
| --- | --- | --- |
|  | Young adults | Older adults |
| *Prop of recall of studied pairs* |  |  |
| Conjunctive – Inclusion | .50 (.07) | .39 (.07) |
| Relational – Inclusion | .51 (.10) | .38 (.07) |
| Conjunctive – Exclusion | .07 (.04) | .12 (.04) |
| Relational – Exclusion | .08 (.05) | .13 (.04) |
| *Controlled processes* |  |  |
| Conjunctive | .43 (.08) | .26 (.07) |
| Relational | .42 (.13) | .25 (.09) |
| *Automatic processes* |  |  |
| Conjunctive | .12 (.06) | .17 (.05) |
| Relational | .14 (.07) | .17 (.05) |

Table 3. Characteristics of the groups in Experiment 2

|  |  |  |
| --- | --- | --- |
|  | Young adults | Older adults |
| Age | 22.7 (2.7) | 66.0 (4.5) |
| Years of education | 14.1 (1.5) | 13.0 (2.9) |
| Gender (F/M) | 10/10 | 12/8 |
| DRSa | - | 139.9 (2.9) |

Note. a Dementia Rating Scale (total score).

Table 4. Experiment 2: Short-term binding performance as a function of group and condition

|  |  |  |
| --- | --- | --- |
|  | Young adults | Older adults |
| *Prop of recall of studied pairs* |  |  |
| Conjunctive – Inclusion | .58 (.13) | .46 (.06) |
| Relational – Inclusion | .56 (.11) | .39 (.07) |
| Conjunctive – Exclusion | .11 (.04) | .14 (.04) |
| Relational – Exclusion | .15 (.08) | .14 (.05) |
| *Controlled processes* |  |  |
| Conjunctive | .46 (.15) | .32 (.09) |
| Relational | .41 (.15) | .25 (.10) |
| *Automatic processes* |  |  |
| Conjunctive | .22 (.07) | .20 (.05) |
| Relational | .26 (.10) | .19 (.05) |

Table 5. Characteristics of the groups in Experiment 3

|  |  |  |
| --- | --- | --- |
|  | Young adults | Older adults |
| Age | 23.2 (3.8) | 71.0 (4.5) |
| Years of education | 14.4 (2.4) | 14.0 (2.8) |
| Gender (F/M) | 11/12 | 12/12 |
| MoCA | - | 29.0 (0.8) |

Table 6. Experiment 3: Short-term binding performance as a function of group and condition

|  |  |  |
| --- | --- | --- |
|  | Young adults | Older adults |
| *Prop of recognition of studied pairs* |  |  |
| Conjunctive – Inclusion | .91 (.07) | .77 (.16) |
| Relational – Inclusion | .92 (.09) | .75 (.16) |
| Conjunctive – Exclusion | .10 (.08) | .25 (.13) |
| Relational – Exclusion | .15 (.13) | .30 (.14) |
| *Controlled processes* |  |  |
| Conjunctive | .81 (.13) | .52 (.26) |
| Relational | .77 (.18) | .44 (.28) |
| *Automatic processes* |  |  |
| Conjunctive | .57 (.22) | .52 (.23) |
| Relational | .62 (.14) | .58 (.14) |

Figure captions

Figure 1. Exp. 1: Schematic of the four conditions of the short-term binding task.

Figure 2. Exp. 2: Schematic of the four conditions of the short-term binding task.

Figure 3. Exp. 3: Schematic of the four conditions of the short-term binding task.

1. The ability to temporarily maintain a small quantity of associations, that we refer to here as “binding in visual short-term memory” or “ short-term binding”, is also often named “binding in visual working memory” (e.g., Rhodes et al., 2016) or “temporary binding” (e.g., Brown et al., 2017). [↑](#footnote-ref-1)