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Ageing and feature binding in visual working memory: The role of presentation time.

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Abstract

A large body of research has clearly demonstrated that healthy ageing is accompanied by an associative memory deficit. Older adults exhibit disproportionately poor performance on memory tasks requiring the retention of associations between items (e.g. pairs of unrelated words). In contrast to this robust deficit, older adults' ability to form and temporarily hold bound representations of an object's surface features, such as colour and shape, appears to be relatively well preserved. However, the findings of one set of experiments suggest that older adults may struggle to form temporary bound representations in visual working memory when given more time to study objects (Brown & Brockmole, 2010). However, those findings were based on between participant comparisons across experimental paradigms. The present study directly assesses the role of presentation time in younger and older adults' ability to bind shape and colour in visual working memory using a within participant design. We report new evidence that giving older adults longer to study memory objects does not differentially affect their immediate memory for feature combinations relative to individual features. This is in line with a growing body of research suggesting that there is no age-related impairment in immediate memory for colour-shape binding.

Keywords: Cognitive Ageing, Feature Binding, Visual Working Memory

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Accurate memory for complex objects or events requires that many different types of information are bound together and held as integrated representations. It is often suggested that older adults have an impaired ability to bind the various aspects of multi-factorial objects or events, and that this, to some extent, underlies their poor performance on tasks assessing working memory and episodic memory (e.g. Chalfonte & Johnson, 1996; Naveh-Benjamin, 2000; Shing et al., 2010; Sander, Lindenberger, & Werkle-Bergner, 2012). This proposition has proven useful in understanding the pronounced decline of episodic memory with age (see, Shing et al., 2010, for a review). Older adults show a pronounced deficit when required to learn and remember associations between items (e.g. face and name) over and above any deficit exhibited for those items individually. This *associative deficit* is robust and has been demonstrated across a variety of stimuli (Naveh-Benjamin, 2000; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003; Old & Naveh-Benjamin, 2008b; Spencer & Raz, 1995; see Old & Naveh-Benjamin, 2008a for a review and meta-analysis). Although it has mainly been studied using long-term memory paradigms, this associative deficit has recently been shown across short retention intervals (even immediate recognition), suggesting that it arises during the initial encoding and maintenance of associations in working memory (Chen & Naveh-Benjamin, 2012).

Given the success of the associative deficit in helping to understand the decline of episodic memory with age, considerable interest has been devoted to identifying whether qualitative changes to representational format can help explain decline in visual working memory[1] (VWM) performance with age (Brockmole & Logie, 2013; Brockmole, Parra, Della Sala, & Logie, 2008; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Johnson, Logie, & Brockmole, 2010; Peich, Husain, & Bays, 2013). This work has focused on older adults' ability to form and maintain integrated temporary representations of objects defined by conjunctions of features (e.g. colour and shape), therefore assessing the ability to bind features *within* items rather than associations *between* items (Ecker,

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[1] The term 'visual working memory' is used to refer to rather different concepts in the literature on visual perception and attention compared with the literature on conceptual models of working memory or the literature on individual differences in working memory capacity. We assume that visual working memory comprises a modality-specific memory system that is part of a broader multiple component working memory (Logie, 2011), and this reflects our use of the term here. For present purposes this is broadly consistent with how the term visual working memory is used in the literature on temporary feature binding.

Maybery, & Zimmer, 2013; Piekema, Rijpkema, Fernandez, & Kessels, 2010; see, Zimmer,

Mecklinger, & Lindenberger, 2006 for a review and discussion of this distinction).

In contrast to the literature on associative memory, age-related binding deficits in VWM have

proven less consistent (for a review see Allen, Brown, & Niven, 2013). In studies in which location is

a relevant feature, and participants are required to retain the binding between object identity (e.g.

colour or form) and spatial location, findings have been mixed. Some studies find that older adults are

more likely to miss changes to the exact pairing of object and location (Cowan et al., 2006; Mitchell,

Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000) or

erroneously recall stimuli from unprobed locations (Peich et al., 2013), consistent with the idea that

older adults are more likely to 'mis-bind' object and location. However, other investigations have

failed to find a disproportionate effect of age on tasks requiring the maintenance of 'what was where'

(Bopp & Verhaeghen, 2009; Olson et al., 2004). It has also been suggested that older adults' mis-

binding errors may be explained by a failure to retain object identity, as Pertzov, Heider, Liang, and

Husain (2015) recently found that, when correcting for age differences in object recognition, there

was no effect of age on the ability to recall object-location bindings. Thus, the effect of age on object-

location binding is unclear. Moreover, when location is rendered task irrelevant (by randomly moving

items between study and test) and participants are required to form temporary bindings between an

object's surface features (e.g. colour and shape) many studies find little or no evidence for a

differential age effect on binding over and above any effect of age on the ability to remember

individual, unbound features such as colour only or shape only (Brockmole & Logie, 2013;

Brockmole et al., 2008; Parra, Abrahams, Logie, & Della Sala, 2009).

For example, Brockmole et al. (2008) used the change detection task in which participants

were required to remember a briefly presented array of objects over a short blank interval (1 second)

in order to detect a change in a subsequent test array. In some blocks of trials participants were

required to detect changes to the individual features (either colour only or shape only), and in other

blocks they were required to detect changes to the combination (or binding) of features between the

two arrays. Overall change detection performance was poorer in the older, relative to the younger,

group reflecting reduced VWM capacity with age (see also, Jost, Bryck, Vogel, & Mayr, 2011;

Sander, Werkle-Bergner, & Lindenberger, 2011). However, the older group's performance in the binding condition was not significantly different from the shape only condition, suggesting that older adults are still able to bind features in VWM, with performance limited by the most difficult feature dimension. This general pattern of results has been shown in multiple studies (Parra et al., 2009a; see, Brockmole & Logie, 2013; Brockmole et al., 2008, Experiment 3, for evidence using recall). This is particularly notable given that older adults with Alzheimer's disease and even those with a gene mutation that will lead to the onset of Alzheimer's disease in the future exhibit a large binding deficit in similar tasks (e.g. Parra et al., 2009b; 2010; 2011).

However, the findings of Brown and Brockmole (2010) suggest that there may be certain conditions under which healthy older adults struggle to form temporary bound representations in VWM. They conducted two experiments examining the role of attentional resources in younger and older adults' ability to bind shape and colour in VWM. In their first experiment they compared the effect of counting backwards in threes during each change detection trial with a less demanding concurrent articulatory suppression condition. In the second experiment they compared simultaneous and sequential presentation of memory objects, motivated by the finding that bindings are more susceptible to interference than individual features (Allen, Baddeley, & Hitch, 2006; Logie, Brockmole, & Vandenbroucke, 2009; Wheeler & Treisman, 2002). In both experiments the manipulations showed evidence of disrupting performance for shape-colour binding to a greater extent than individual features (although see, Allen, Hitch, Mate, & Baddeley, 2012), but this was true for both age-groups. However, a comparison of the two experiments yielded an interesting pattern of results. In Experiment 1 there was no evidence of an age-related binding deficit; that is, there was no significant interaction between age-group and memory condition (shape only, colour only, and shape-colour binding). By contrast, in Experiment 2 there was evidence for an age-related binding deficit in the form of an age by memory condition interaction, with binding showing a larger age effect than individual features alone.

As Brown and Brockmole note, a key difference between the two experiments was the duration for which memory objects were presented. In Experiment 1 the memory array was presented for 900 ms, whereas for Experiment 2 this was increased to 1500 ms, due to sequential presentation in

the more demanding experimental condition. Therefore, this surprising finding may reflect the temporal nature of feature binding in VWM. For example, it has been proposed that short stimulus exposures may accommodate an automatic binding mechanism based largely on early perceptual processing. On the other hand, longer exposures may allow for the deployment of general attentional resources to process and elaborate on the different feature combinations present in an array (Allen et al., 2006, 2012). Studies assessing the role of general attentional (or executive) resources in feature binding have tended to use short stimulus exposures (< 1 second) and have consistently shown that VWM for feature bindings is no more impaired by demanding concurrent tasks than VWM for individual features (e.g., Allen et al., 2006, 2012; Johnson, Hollingworth, & Luck, 2008; C. C. Morey & Bieler, 2013; Yeh, Yang, & Chiu, 2005). On the other hand an unpublished study by Elsley and Parmentier (cited in Elsley & Parmentier, 2009) presented memory objects for 2000 ms and found that concurrent maintenance of words disrupted VWM for colour-shape bindings to a greater extent than for shapes alone.

While this work is far from conclusive it is suggestive of a greater role for general attentional resources in temporary feature binding in VWM when stimulus exposure is extended. Older adults often exhibit deficits on tasks requiring effortful or controlled processing whereas tasks relying on relatively automatic processes are largely spared (Craik & Bialystok, 2006; Craik & Byrd, 1982). Therefore, if the formation of integrated representations becomes more demanding of attention (more 'active', Allen et al., 2006) with extended presentation time, it is conceivable that older adults are less able to make use of the extra time (e.g. Craik & Rabinowitz, 1985). Given the pronounced feature binding deficit observed in early Alzheimer's disease, and the implications this has for the assessment of the disease (Parra, 2014), it is important to establish conditions under which healthy older adults exhibit a reliable binding deficit.

The effect of presentation time on older adults' ability to bind features was not of direct interest for Brown and Brockmole's (2010) experimental manipulations. Consequently, the comparison was made between experiments, that is, between participants, and across two different experimental paradigms. A within participant comparison across directly comparable experimental conditions would make for a stronger test. Therefore, the present study set out to directly assess the

effect of presentation time on younger and older adults' ability to bind the shape and colour of objects in VWM. We are aware of at least one, as yet unpublished study that has failed to find an effect of presentation time on older adults' binding performance using the same durations as Brown and Brockmole (900 and 1500 ms; L. A. Brown, personal communication). Therefore, we decided to opt for a longer presentation time (2500 ms) in order to increase our chance of finding an age-related effect if one exists.

Method

Participants

Twenty-four younger adults (15 female), aged 18–25 (*M* = 21.37, *SD* = 2.10), were recruited from the student population of the University of Edinburgh and were given either course credit or £5 in return for participation. The older adult group comprised 24 members (16 female) of the University of Edinburgh, Psychology research volunteer panel drawn from the local community, aged 67–78 (*M* = 73.17, *SD* = 3.69), each given £5 in return for participation. Prior to participating in the main experiment all older adults completed the Mini Mental State Examination (MMSE: Folstein, Folstein, & McHugh, 1975) and both age-groups completed the National Adult Reading Test (NART: Nelson, 1982) in order to obtain an estimate of verbal IQ. Normal colour vision was confirmed using a colour blindness test (Dvorine, 1963).

All older adults scored 27 or above on the MMSE (*M* = 29.46, *SD* = 0.93). Predicted verbal IQ scores from the NART were significantly higher in the older group (*M* = 120.18, *SD* = 5.06) than the younger group (*M* = 108.40, *SD* = 5.44), *t*(46) = 7.77, *p* < 0.001. Years of education on the other hand did not differ significantly between groups (Older: *M* = 16.25, *SD* = 3.28; Younger: *M* = 16.15, *SD* = 2.18), *t*(46) = 0.13, *p* = 0.90.

Stimuli and Apparatus

In line with the experiments of Brown and Brockmole (2010) memory arrays consisted of three coloured shapes presented on a grey background. Each object in the memory array was constructed by combining one of six colours (blue, green, purple, red, turquoise, and yellow) with one of six shapes (arrow, diamond, circle, cross, heart, and triangle), randomly without replacement. Test arrays

consisted of a single probe, the nature of which differed according to the memory condition (colour, shape, or binding). When assessing VWM for colour the test object was a 'blob' shape filled in a single colour. For blocks assessing shape memory the test item was a black outline of a shape filled in to match the background. Finally for binding trials the test object was a coloured shape (see Figure 1). Stimuli were presented on a 22" LCD monitor. Each object measured approximately 2 cm^2. Objects in the memory array were presented in a row separated centre-to-centre by approximately 5 cm and were centred 3 cm above a central fixation cross. Test items appeared in analogous positions 3 cm below the central fixation. The location occupied by the test item was chosen at random. The experimental sequence was implemented in E-Prime (Schneider, Eschman, & Zuccolotto, 2002).

Procedure

The general trial procedure used in the change detection task is shown in Figure 1. Participants initiated each trial, when ready to do so, by pressing the spacebar on the keyboard. They were then presented with a randomly generated number, between 20 and 99, for 2 seconds which they were required to repeat aloud at a steady pace throughout the trial, until the response was made. The experimenter recorded the number of articulations made on each trial and ensured a stable rate of articulation. Following the number a blank central fixation screen was presented for 1 second and the fixation cross remained visible throughout the trial. The memory array was then presented for 900 or 2500 ms depending on the current block. Following a 1 second retention interval the test array was presented and remained visible until the response was made. Participants were required to indicate whether the test item had appeared in the previous memory array or if a change had occurred by pressing either the '*z*' key (labelled 'YES') or the '*m*' key (labelled 'NO'), respectively. For change trials in the individual feature conditions (colour or shape only) the test object was randomly selected from the three remaining colours or shapes not present in the memory array. For binding change trials the test item was created by recombining a shape and colour from the initial memory array that had not appeared together (see Figure 1 for an example). This 'feature swap' method ensures that participants are required to remember the binding of shape and colour in order to detect a change rather than the features individually (cf. Chalfonte & Johnson, 1996).

The experiment was divided into 6 blocks combining the 2 presentation times and 3 memory conditions. Participants completed all memory conditions at a given presentation time before moving on to the next. Half of the participants in each age-group completed the 900 ms condition first and the other half completed the 2500 ms condition first. The order of memory conditions was counterbalanced with the constraint that each participant completed the memory tasks in the same order at each presentation time. Each block began with 6 practice trials followed by 36 experimental trails with breaks provided between blocks. In each block 50% of trials were change trials and 50% were no-change trials.

Results

Accuracy. Table 1 presents the proportion correct responses given by the younger and older adults in each of the experimental conditions across trials in which there was a change and where there was no-change. These data were entered into a 3 (memory condition) × 2 (group) × 2 (presentation time) × 2 (trial type: change or no-change) mixed ANOVA which is reported in Table 2. There were significant main effects of age-group, with younger adults producing more correct responses ($M = 0.88$) than older adults ($M = 0.82$), and presentation time, with longer presentation leading to slightly better performance (900 ms: $M = 0.84$; 2500 ms: $M = 0.86$). There was also a large main effect of memory condition as performance was greatest in the colour condition ($M = 0.94$) followed by shape ($M = 0.86$) and then binding ($M = 0.76$). Trial type (change or no-change) did not produce a main effect ($F < 1$) but it did produce a significant interaction with memory condition. To probe this further we conducted separate focused ANOVAs comparing two memory conditions at a time assessing the evidence for the trial type by memory condition interaction. The interaction was significant for the contrast between colour and binding, $F(1, 46) = 30.00$, $MSE = 0.018$, $p < 0.001$, $\eta^2_P = 0.395$, and between shape and binding, $F(1, 46) = 19.27$, $MSE = 0.017$, $p < 0.001$, $\eta^2_P = 0.295$. However, when contrasting colour and shape the interaction was no longer significant, $F(1, 46) = 2.10$, $MSE = 0.011$, $p = 0.15$, $\eta^2_P = 0.044$. From this it is clear that for individual features performance was better when a change occurred (colour: $M = 0.96$; shape: $M = 0.87$) relative to when no-change occurred (colour: $M = 0.91$; shape: $M = 0.85$), whereas for binding the opposite was true (change: $M = 0.71$; no-change: M

= 0.81). Finally, the interaction between age-group and trial type was marginal ($p = 0.054$), providing slight evidence that the effect of age was larger for no-change trials (younger: $M = 0.90$; older: $M = 0.81$) relative to change trials (younger = 0.86, older = 0.84). None of the remaining interactions reached significance, including those containing age-group and memory condition (see Table 2).

Previous studies assessing the effect of age on feature binding have often relied on failure to reject the null as evidence for the age-invariance of feature binding. Therefore, in order to quantify the strength of evidence *for* or *against* the presence of age-group interactions we also present default Bayes factors (Rouder, Morey, Speckman, & Province, 2012). These were calculated using the *BayesFactor* package in *R* (R. D. Morey & Rouder, 2013; R Core Team, 2013). The strength of evidence for an interaction was assessed by comparing a linear model containing the interaction of interest with its corresponding main effects to a model containing only the main effects[2]. Consequently, a Bayes factor (*BF*) greater than 1 signifies that the data are more probable under the interaction model, whereas a *BF* smaller than 1 signifies that the data are more probable under the null, main effects only, model.

Taking this approach to assess the strength of evidence for or against interactions of interest we find substantial evidence against an interaction between age-group and presentation time, with the null model favoured by a factor of approximately 7 ($BF = 0.136 \pm 1.18\%$). As in the conventional analysis of variance the weight of evidence was in favour of the interaction between age-group and trial type ($BF = 3.652 \pm 1.34\%$) and against the three way interaction with presentation time ($BF = 0.178 \pm 1.38\%$). Turning to the crucial interactions involving age-group and memory condition we find substantial evidence against the suggestion of an age-group by memory condition interaction as the null model was preferred by a factor of approximately 6 ($BF = 0.159 \pm 1.27\%$). The null model was also preferred, by a factor of over 8, when considering the age by condition by trial type interaction ($BF = 0.114 \pm 1.27\%$). For the crucial three way interaction between age-group, memory condition, and presentation time we find even stronger evidence against the interaction with the null model over 10 times more likely than the alternative including the interaction ($BF = 0.092 \pm 1.96\%$).

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[2] We used the *lmBF* function from the *BayesFactor* package to set up these specific contrasts. We used the default settings with the exception of changing the number of Monte Carlo integration samples used to compute the Bayes factors in order to keep proportional error below 2%.

Finally, for the four way interaction the null model was marginally favoured over the model including the interaction ($BF = 0.452 \pm 1.57\%$).

      Discrimination. While inspecting accuracy across change and no-change trials is instructive, interpretation can be problematic as these values are influenced by the response bias exhibited by the observer. For example, if observers exhibit a bias towards responding change this will be reflected as both an increase in hit rate but also a reduced correct rejection rate (more false alarms). It is possible that younger and older adults exhibit different levels of response bias in the different memory conditions which may obscure differences in sensitivity. As our main interest is in participants' ability to distinguish change and no-change trials across the different memory conditions it is preferable to use a measure of discriminability (or sensitivity) to assess performance uncontaminated by response bias. In doing so there are many measures to choose from, each derived from a different underlying conception of recognition memory. The commonly used measure, *d'*, comes from a signal detection theory model which postulates that change and no-change trials form two (Gaussian equal variance) distributions along a continuum of familiarity (with no-change trials generally producing stronger familiarity). The separation of these distributions, *d'*, denotes the sensitivity of the observer. The measure *A'* comes from a similar tradition but aims to circumvent the distributional assumptions associated with *d'*. In contrast to these graded familiarity models of recognition, corrected recognition (hits minus false alarms) is based on a two-high threshold model which postulates discrete states; either knowing that the test item is the same or different, or being in a state of uncertainty and guessing whether a change has occurred (see, Snodgrass & Corwin, 1988).

      While Brown and Brockmole (2010) analysed performance in terms of *A'*, in the present analysis we opt for corrected recognition (hit rate minus false alarm rate). There are a couple of reasons for this; values of *A'* are dependent on the bias exhibited by the observer, such that greater bias in either direction results in underestimation of sensitivity (Pastore, Crawley, Berens, & Skelly, 2003; Snodgrass & Corwin, 1988). This dependence presents a problem in the current data as an analysis of the corresponding bias measure, *B''*, yielded main effects of memory condition, $F(2, 92) = 40.08$, $MSE = 0.017$, $p < 0.001$, $\eta^2_P = 0.466$, presentation time, $F(1, 46) = 9.07$, $MSE = 0.009$, $p < 0.05$, $\eta^2_P = 0.165$, and, crucially, age-group, $F(1, 46) = 22.67$, $MSE = 0.028$, $p < 0.001$, $\eta^2_P = 0.33$.

There were no significant interactions ($Fs < 1.9$, all $ps > 0.15$). Further, there is evidence that, when highly discriminable stimuli are used, change detection performance appears to be based on all-or-none recognition (Rouder et al., 2008), consistent with a threshold model. However to ensure that our choice of corrected recognition does not unduly affect our conclusions we conducted analysis on other common measures of performance (d', proportion correct, and importantly A') which are presented in Supplementary Material. The choice of outcome measure does not change the main conclusions of the present study relative to the analysis of corrected recognition, although this is not always the case (see, Allen et al., 2012).

Corrected recognition across the experimental conditions is presented in Figure 2. A $3 \times 2 \times 2$ mixed ANOVA revealed significant main effects of age-group, $F(1, 46) = 5.91$, $MSE = 0.154$, $p < 0.02$, $\eta^2_P = 0.114$, presentation duration, $F(1, 46) = 8.69$, $MSE = 0.020$, $p < 0.01$, $\eta^2_P = 0.159$, and memory condition, $F(2, 92) = 126.45$, $MSE = 0.023$, $p < 0.001$, $\eta^2_P = 0.733$. The younger group ($M = 0.76$) outperformed the older group ($M = 0.65$) and scores were slightly higher following longer presentation of memory objects (900 ms: $M = 0.69$; 2500 ms: $M = 0.73$). Corrected recognition was greatest in the colour condition ($M = 0.87$), followed by the shape condition ($M = 0.72$), and was lowest in the binding condition ($M = 0.52$). The interactions between age-group and presentation duration [$F(1, 46) = 0.35$, $MSE = 0.02$, $p = 0.55$, $\eta^2_P = 0.008$] and between presentation time and memory condition [$F(2, 92) = 0.45$, $MSE = 0.009$, $p = 0.64$, $\eta^2_P = 0.010$] both did not reach significance. Crucially, neither the interaction between age-group and memory condition [$F(2, 92) = 1.84$, $MSE = 0.023$, $p = 0.16$, $\eta^2_P = 0.038$] nor the three way interaction [$F(2, 92) = 0.89$, $MSE = 0.009$, $p = 0.41$, $\eta^2_P = 0.019$] were significant.

Assessing the strength of evidence against age-group interactions the data are approximately 2 times less likely under the age-group by memory condition interaction model relative to its main effects only model ($BF = 0.516 \pm 0.80\%$)[3]. For the interaction between age-group and presentation time the data were approximately 5 times more likely under the null model ($BF = 0.194 \pm 1.76\%$).

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[3] As shown in supplementary material the analysis of d' revealed much stronger evidence against the age by condition interaction ($BF = 0.117$). The reasons for this are unclear but it is important to note that the analysis of proportion correct and A' yielded Bayes factors of a similar magnitude to corrected recognition ($BFs = 0.502$ and 0.55 respectively).

Finally, for the interaction of primary interest to the present study, the three-way interaction, the data favour the main effects only model by a factor of approximately 6 ($BF = 0.166 \pm 1.98\%$).

Discussion

Studies assessing older adults' ability to remember between-item associations have convincingly demonstrated an associative binding deficit with age (Old & Naveh-Benjamin, 2008a). However, the evidence regarding older adults' ability to combine features within objects (sometimes referred to as conjunctive binding) and retain them for very short time periods has been less clear. Brown and Brockmole (2010) reported two experiments which, taken together, suggested a role for increased presentation time in the emergence of an age-related feature binding deficit. This could plausibly be linked to a greater role for attentional resources to engage in a more active form of feature binding at longer stimulus durations (e.g. Allen et al., 2006), something older adults may struggle with (Craik & Bialystok, 2006). We therefore assessed the effect of presentation time on younger and older adults' ability to bind the colour and shape of objects in VWM.

Using conventional analysis there was no suggestion that age differentially affected VWM for individual features and their combinations, in line with multiple studies addressing this question (Brockmole & Logie, 2013; Brockmole et al., 2008; Parra et al., 2009). Further, there was no suggestion that increasing study time changed this. The present work also goes beyond previous investigations as we were able to quantify the evidence against the age-group interactions in the present data using default Bayes factors (Rouder et al., 2012). In the case of the three way interaction between all variables in our analysis of corrected recognition the evidence against the interaction was 'substantial' (Jeffreys, 1961), as the data were over 6 times more likely under the null. While our data cannot adjudicate on whether or not temporary feature binding becomes more 'active' with longer encoding time these findings are more consistent with the suggestion that presentation time does not differentially affect younger and older adults' VWM for individual features or feature bindings. Furthermore, whilst the evidence against interactions involving age-group and memory condition was, of course, far from conclusive it was always the case that the data were more likely under models omitting these interactions.

It may be that small demographic differences between the sample recruited for the present study and that of Brown and Brockmole, especially their Experiment 2, may account for the absence of the age-group interaction. Our sample had received a slightly higher mean years of education compared to Brown and Brockmole's sample in their Experiment 2 (16.25 versus 13.81) and also obtained a higher mean estimate of verbal IQ from the NART (120.18 versus 115.63). Despite this, we suspect that these slight differences in years of education and verbal IQ cannot account for the absence of the crucial interaction, especially given that these characteristics were well matched between the two experiments of Brown and Brockmole (2010), one of which did find a binding deficit. Moreover, recent studies of VWM binding in populations with different demographic features and health status confirmed that age and education did not yield significant differences between control participants nor did they impact on performance in affected individuals (Parra et al., 2011). Our conclusion, that increasing presentation time does not lead to an age-related colour-shape binding deficit, is also strengthened by another recent, unpublished study assessing the effect of presentation time on older adults' binding performance using identical durations to Brown and Brockmole (2010) which also failed to find an age-related binding deficit (L. A. Brown, personal communication). Further, the present experiment increased the disparity between the shorter and longer presentation times and therefore was, arguably, more likely to find an effect of presentation time.

Explaining why Brown and Brockmole (2010) did find evidence of an age-related binding deficit in their second Experiment is a difficult task. While we suspect differences in verbal IQ and years of education are insufficient to explain this there remain other sample characteristics that may contribute to the appearance of a binding deficit. As detailed in the Introduction a specific colour-shape binding deficit appears to be a marker of early Alzheimer's disease (Parra et al., 2009b), and has even been observed in a familial variant of the disease approximately 10 years before conversion (Parra et al., 2010). Whether a random sample of healthy older people show a binding impairment in the group aggregate score would then depend on how many might be at risk for developing dementia, even if they are otherwise asymptomatic at the time of testing. This is an hypothesis that we plan to address in our future research. However, it appears clear that in most groups of healthy older adults any binding impairment in temporary memory is either not present or too small to be statistically

reliable (Brockmole et al., 2008; Brown & Brockmole, 2010, Exp 1; Parra et al., 2009a), and may be

one of the cognitive abilities that is relatively well preserved across the healthy adult lifespan (for a

review see Logie, Horne and Pettit, 2015).

The difficulty in obtaining evidence for an age-related binding deficit for colour-shape

conjunctions stands in stark contrast to the ubiquity of the associative deficit in memory for relations

between-items (Chen & Naveh-Benjamin, 2012; Old & Naveh-Benjamin, 2008a) and previous

demonstrations of object-location binding deficits in VWM (Cowan et al., 2006; Mitchell et al., 2000a,

2000b; Peich et al., 2013), although this has proven less consistent (Bopp & Verhaeghen, 2009; Olson

et al., 2004; Pertzov et al., 2015). In attempting to explain this disparity it is useful to draw a

distinction between binding features within-items, where the features define the intrinsic

characteristics of an object, and retaining pairings of distinct items or contextual features

accompanying an item, where the binding is between extrinsic features. This distinction has often

been made in the long-term memory literature and is increasingly being recognised in research on

working memory (see Zimmer et al., 2006, for a review). For example, Ecker, Maybery, and Zimmer

(2013) found that when shape and colour were presented as within-item relations (with the colour

filling the shape) there was evidence that shape was implicitly bound to colour in VWM. That is, task

irrelevant changes in colour affected change detection accuracy for shape. However, when the

features were presented as a between-item relation, with the foreground shape presented apart from its

extrinsic background colour, there was no evidence for this obligatory binding. Other studies of

VWM have also demonstrated that simple features are less readily associated when presented as

separate items relative to when they are present within the same object (e.g. Delvenne & Bruyer, 2004;

Xu, 2002). Further there is some evidence that binding items to their spatial location requires

additional attentional resources beyond retaining item or location information alone (Elsley &

Parmentier, 2009; although see Cowan et al., 2006). The relative automaticity of binding conjunctions

of features within-items (see also, Allen et al., 2006, 2012; Johnson et al., 2008; C. C. Morey & Bieler,

2013; Yeh et al., 2005) may help explain the difficulty in obtaining evidence for an age-related deficit

(Craik & Bialystok, 2006; Craik & Byrd, 1982). On the other hand associating disparate features into

a coherent representation may be more cognitively demanding (see Zimmer et al., 2006) and consequently more susceptible to the effects of age.

Another crucial, and possibly related, factor that may contribute to discrepant findings is the role of the medial temporal lobes in these different forms of working memory binding. In the episodic long-term memory literature older adults' poor associative memory has been linked to dysfunction of the medial temporal lobes, particularly the hippocampus, and their functional relationship with the frontal lobes (see Shing et al., 2010, for a review). The findings of several neuroimaging studies suggest that the hippocampus participates in the temporary maintenance of between-item associations, for example pictures of faces and houses (Piekema, Kessels, Rijpkema, & Fernandez, 2009; Piekema et al., 2010), and retaining object-location bindings in working memory (Mitchell et al., 2000b; Piekema, Kessels, Mars, Petersson, & Fernandez, 2006; although see Piekema et al., 2010). Hippocampal dysfunction may also help explain demonstrations of an age-related object-location binding deficit (e.g. Cowan et al., 2006; Mitchell et al, 2000a; Peich et al., 2013). Mitchell et al. (2000b) found that while their younger group exhibited left hippocampal activity specific to the maintenance of object-location pairings in VWM their older adult group did not exhibit this binding specific activity. By contrast retaining pairings of features within-items does not appear to depend on the medial temporal lobes. A recent fMRI study assessing colour-shape binding using a change detection paradigm found binding specific activation associated with the left lateral occipital complex and inferior parietal cortex, but crucially no binding specific activation was observed in the medial temporal lobes (Parra, Della Sala, Logie, & Morcom, 2014; see also, Piekema, Rijpkema, Fernandez, & Kessels, 2010). Converging evidence also comes from studies of amnesic patients who despite pronounced hippocampal damage show preserved colour-shape binding performance (Baddeley, Allen, & Vargha-Khadem, 2010; Parra et al., 2013).

Therefore, evidence from different levels of analysis supports a distinction between different forms of working memory binding and suggests reasons why some may be more age-sensitive than others. Namely binding between-items appears to be cognitively demanding and associated with hippocampal activity whereas binding within-items appears to be relatively automatic and not hippocampus dependent. However, as noted by Chen & Naveh-Benjamin (2012) there are other

methodological differences between studies that do find age-related binding deficits and those who do not. For example, the former tend to use more complex, ecologically valid, stimuli whereas the latter (including the present study) use simple features. Future behavioural and neuroimaging studies of age-related changes to short-term recognition memory would greatly benefit from comparing relational and conjunctive binding mechanisms directly.

Further, while the evidence reviewed above gives some reason to suspect that binding object to location shares some features with between-item binding, namely involvement of the hippocampus (Mitchell et al., 2000b; Piekema et al., 2006) and disruption by attentional distraction (Elsley & Parmentier, 2009), there are studies that have failed to demonstrate this. For example in an fMRI study comparing different forms of VWM binding, Piekema et al. (2010) found no location binding specific activation in the hippocampus and in two experiments with younger adults Cowan et al., (2006) found no-evidence that colour-location binding was differentially disrupted by a concurrent task. These mixed findings correspond with the mixed findings regarding older adults' ability to retain object-location combinations in VWM discussed in the Introduction. Again differences in methodology prevent concrete conclusions on the causes of these discrepant findings. Therefore, investigating the role of attentional resources, the medial temporal lobes, and ageing in the efficacy of object-location binding in VWM remains a fruitful area for research.

Further, while the effect of age on the binding of surface features in VWM has been examined under various experimental manipulations; such as recall rather than recognition (Brockmole & Logie, 2013; Brockmole et al., 2008, Experiment 3), under attentional load (Brown & Brockmole, 2010, Experiment 1), sequential presentation of memory objects (Brown & Brockmole, 2010, Experiment 2), and varying retention intervals (Brockmole et al., 2008, Experiment 3) there still remain conditions under which a large, reliable surface feature binding deficit may occur. As mentioned in the Introduction it has been shown that while bound representations of shape and colour are formed relatively automatically they are fragile and susceptible to overwriting from subsequent stimuli (e.g. Allen et al., 2006; Logie et al., 2009; Ueno, Allen, Baddeley, Hitch, & Saito, 2011; Wheeler & Treisman, 2002). For example, Ueno et al. (2011) presented a task irrelevant visual suffix following an array of to-be-remembered items and found that, when the suffix was made of features from the

same pool as the study items, change detection performance for shape-colour bindings was disrupted to a greater extent than individual features. The authors propose a filtering process that aims to prevent the suffix from entering VWM and that when this fails the object level (where the link between features is stored) is particularly susceptible to overwriting, whereas representations of individual features survive at a lower 'unbound' level. It seems reasonable to expect that this binding specific suffix effect will be larger in older adults who have been shown to be less able to filter out irrelevant information in VWM tasks (e.g. Jost et al., 2011; Sander et al., 2011). Defining the conditions under which groups of healthy older adults exhibit a binding deficit will not only illuminate the effects of age on VWM but can only serve to strengthen the use of the VWM binding task in the assessment and early identification of Alzheimer's disease.

In summary we assessed the effect of increasing study time for a change detection task on younger and older adults' ability to form bound temporary representations in VWM. The amount of time given to participants did not differentially affect their ability to detect binding changes relative to changes of individual features. This is in line with a growing body of evidence showing that the ability to the bind surface features of objects in VWM is largely unaffected by age (Brockmole et al., 2008; Brockmole & Logie, 2013; Parra et al., 2009a; see Allen et al., 2013 for a review).

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Figure Captions

Figure 1 . Trial sequence during change detection task for colour, shape, and binding.

Note. No-change trials not depicted. Different fill patterns represent different colours and items are
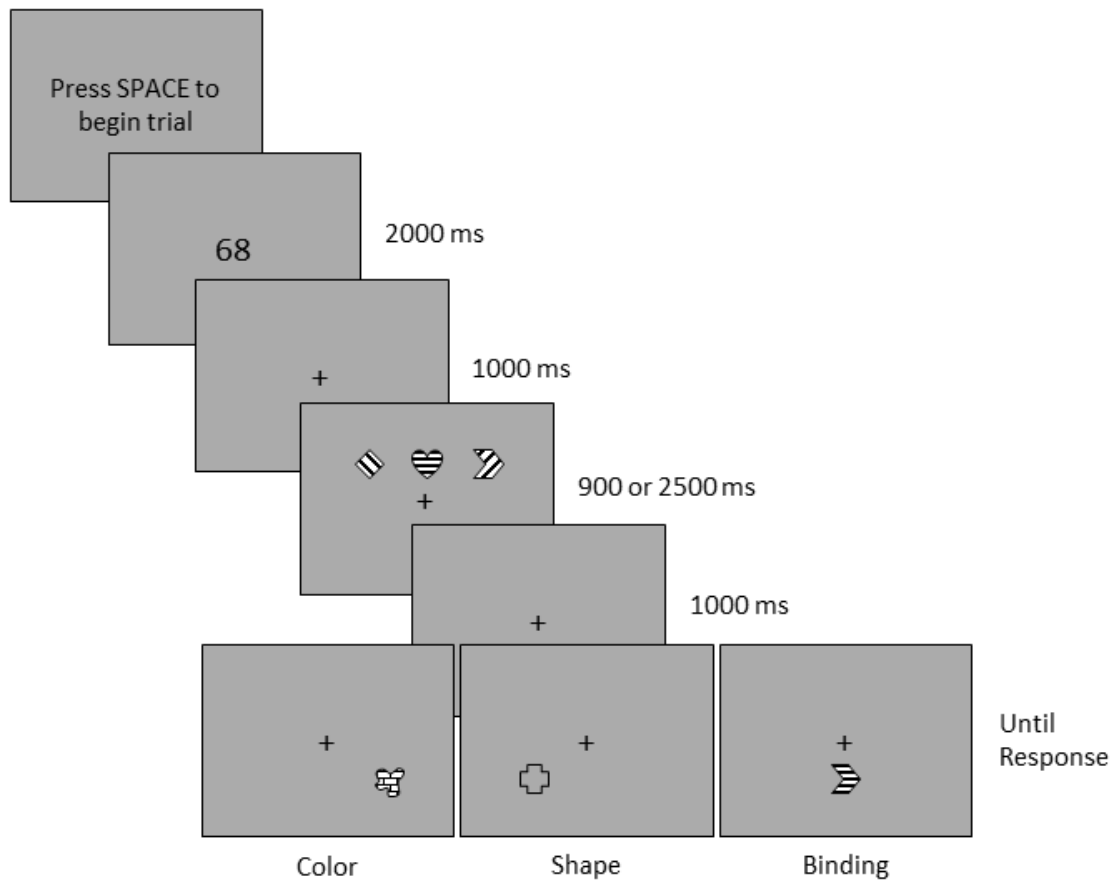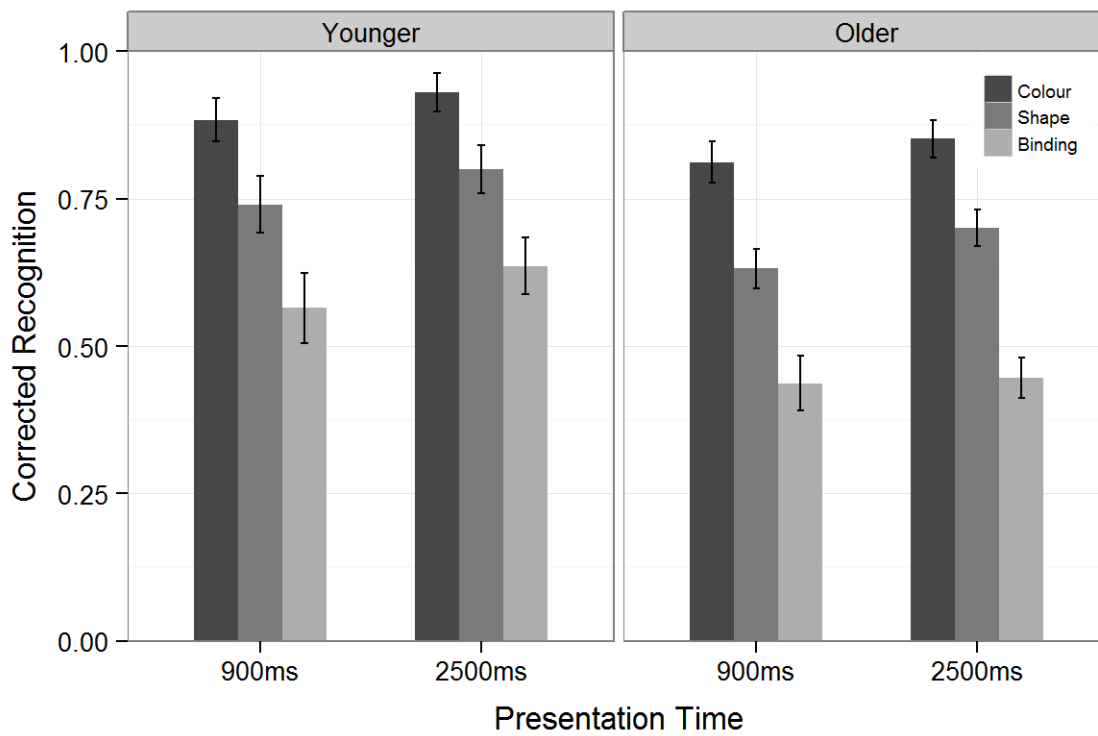
not drawn to scale.

Figure 2 . Corrected recognition across groups and experimental conditions.

Note. Error bars represent ± standard error.

Tables

Table 1.

Mean (and standard error of the mean) proportion correct responses across age-groups and experimental conditions split by change and no-change trials.

		Presentation time			
		900 ms		2500 ms	
Age Group	Memory Condition	Change	No-change	Change	No-change
Younger	Colour	0.95 (.02)	0.93 (.02)	0.97 (.02)	0.97 (.02)
	Shape	0.89 (.02)	0.85 (.03)	0.89 (.04)	0.91 (.02)
	Binding	0.72 (.04)	0.85 (.03)	0.76 (.03)	0.87 (.03)
Older	Colour	0.96 (.02)	0.86 (.03)	0.98 (.01)	0.87 (.03)
	Shape	0.83 (.03)	0.80 (.02)	0.88 (.02)	0.82 (.02)
	Binding	0.71 (.04)	0.73 (.04)	0.67 (.03)	0.78 (.02)

Table 2.

Results of a 2 (age group) × 3 (memory condition) × 2 (presentation time) × 2 (trial type) analysis of variance on accuracy (proportion correct).

Effect	df	F	MSE	p	η^2_P
Age Group	1, 46	5.91	0.077	0.019	0.114
Memory Condition	2, 92	126.45	0.012	<0.001	0.733
Presentation Time	1, 46	8.69	0.010	0.01	0.159
Trial Type	1 , 46	0.05	0.033	0.82	0.001
Age × Condition	2, 92	1.84	0.012	0.16	0.038
Age × Presentation Time	1, 46	0.35	0.010	0.56	0.008
Age × Trial Type	1, 46	3.91	0.033	0.05	0.078
Condition × Presentation Time	2, 92	0.45	0.005	0.64	0.001
Condition × Trial Type	2, 92	19.37	0.015	<0.001	0.296
Presentation Time × Trial Type	1, 46	2.90	0.004	0.10	0.059
Age × Condition × Presentation Time	2, 92	0.89	0.005	0.41	0.019
Age × Condition × Trial Type	2, 92	0.56	0.015	0.57	0.012
Age × Presentation Time × Trial Type	1, 46	<0.01	0.004	0.95	<0.001
Condition × Presentation Time × Trial Type	2, 92	0.10	0.010	0.90	0.002
Age × Condition × Presentation Time × Trial Type	2, 92	2.22	0.010	0.12	0.046