

Chapter 6

AGING AND VISUAL FEATURE BINDING IN WORKING MEMORY

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ABSTRACT

This chapter examines the question of how the features or elements (e.g. shape, color, or spatial location) of a stimulus that is encountered in the visual environment are bound together in working memory to form an integrated representation. We first briefly review recent research on this topic in healthy young adults, examining the factors that determine successful encoding and retention in working memory. A particular focus of the chapter concerns how this key cognitive process (or set of processes) might vary as a function of healthy cognitive aging, and of neuropsychological disorders typically associated with aging (e.g. Alzheimer's disease). It appears that while older adults typically show associative deficits in long-term memory, age-related binding deficits in working memory are somewhat inconsistent in nature, and may depend to some extent on the form of binding being examined.

INTRODUCTION

Previous research on working memory (WM) has often focused on how we process, store and retrieve individual elements, such as form, color, size, or location (in visuospatial memory), and meaning or phonological form (in auditory-verbal memory). In a similar vein, a large majority of work has examined memory for information encountered within a single modality (e.g. vision or audition). This has developed at least partly through efforts to retain simplicity of design and interpretation. As such, classic models of WM (e.g. Baddeley and Hitch, 1974; Logie, 1995) focused on capturing distinctions between elements and between modalities. However, it is clearly also important to explore processing of more complex

stimuli, including items and episodes that consist of multiple conjunctions of elements, both within and between modalities. This is often how information is encountered and indeed consciously experienced in the real world. For example, items in the visual environment typically vary along multiple dimensions such as shape and color; how do we not only perceive but also remember that the apple was red and the leaf green, rather than vice versa? This issue of information binding is a broad one, applying across contexts, domains, and forms of information, as well as having precise and meaningful applications. For example, how does a patient on multiple courses of medication remember, for example, the shape and color of the pill they have taken? By examining such questions, we can develop more sophisticated and comprehensive models of function and structure. Furthermore, we can utilize the methods and theoretical insights that result in understanding how memory changes as a result of both typical cognitive development and of brain disorders, with the potential aim of developing assessment and rehabilitation tools to assist in identifying and ameliorating associated problems. This chapter will focus for the most part on binding within visuospatial WM, briefly considering some of the key developments on this topic from research on young adults, before examining how binding and relational memory might be characterized in LTM and WM as a function of healthy cognitive aging, and Alzheimer's Disease (AD).

VISUOSPATIAL BINDING IN WORKING MEMORY

Binding in WM has received considerable attention in the last few years. This is partly the result of efforts to resolve the shortcomings of influential WM models in addressing how different forms of binding may operate. For example, the tripartite model described by Baddeley and Hitch (1974) was successful in setting out how simple verbal or visuospatial information is temporarily stored (in the phonological loop and visuospatial sketchpad subcomponents respectively) and manipulated (via the central executive, an attentional control resource). However, Baddeley (2000) noted that this simple model was not able to adequately capture how constituent information is bound into objects within or between modalities, or how this is connected to existing representations in long-term memory. As a result, Baddeley added a fourth component to WM termed the episodic buffer, described as a modality-independent store responsible for binding and acting as the central hub between incoming information and LTM. In order to retain parsimony and generate testable predictions, it was originally assumed that binding within the episodic buffer was an active and effortful process, requiring central executive control. Thus, remembering the conjunctions between shape and color, for example, should be more dependent on attention than simply remembering the individual elements.

In order to test this and related questions, researchers have often adopted variants of a recognition paradigm. This involves an initial presentation of a to-be-remembered display containing target stimuli (e.g. a set of colored shapes), followed (after a short delay) by a test phase. This can be a repetition of the whole display, with participants required to detect whether a change has occurred (e.g. Phillips, 1974; Luck and Vogel, 1997), or a single recognition probe, in which case participants must decide whether this was present in the original display (e.g. Wheeler and Treisman, 2002). Memory for individual features is assessed through judgments of whether a new feature is present at test. This test method has

also sometimes been used as an implicit measure of memory for binding (e.g. Elsley and Parmentier, 2009; Luck and Vogel, 1997), though a more direct method of tapping binding involves judgments of whether specific test combinations of color and shape were part of the original display (with lure trials involving recombined objects (e.g. Allen, Baddeley and Hitch, 2006; Wheeler and Treisman, 2002)). A minority of research has also gone beyond recognition paradigms, using tools such as cued verbal recall and non-verbal reconstruction (e.g. Pertsov, Dong, Peich, and Husain, 2012; Ueno, Mate, Allen, Hitch, and Baddeley, 2011).

Generally using single probe recognition, research to date has failed to consistently support the notion of an attention-demanding binding process in healthy adult participants; adding a demanding concurrent task such as backward counting in decrements of three (aimed at reducing available executive resources) during stimulus presentation has substantial effects on visual memory performance, but does not appear to reliably disrupt shape-color binding any more than memory for the individual features (Allen et al. 2006; Allen, Hitch, Mate, and Baddeley, 2012; but see Brown and Brockmole, 2010). This apparent lack of requirement for attention in encoding bound information has also been extended to contexts in which shape and color are initially presented separately in space or time (Karlsen, Allen, Baddeley, and Hitch, 2010) or across visual and auditory modalities (Allen, Hitch, and Baddeley, 2009). These findings led Baddeley, Allen, and Hitch (2011) to suggest that, at least for simple feature conjunctions encountered in the environment, binding is likely a perceptual process that proceeds relatively automatically, with the episodic buffer (or similar component) a passive recipient of this processing. The constraints that might be applied to this automaticity are yet to be clearly mapped out, however; it may be that binding, in certain forms and contexts, is in fact particularly effortful. For example, Ecker, Maybery, and Zimmer (2013) have recently argued that, while intrinsic binding (between elements that are part of the same perceptual unit or 'object') may proceed relatively automatically, extrinsic binding (between different contextual elements, that are part of the same episode but not the same stimulus) may require additional cognitive resources.

It is also important to consider how features and their conjunctions are retained in memory, once encoded. Luck and Vogel (1997; Vogel, Woodman, and Luck, 2001) found evidence to indicate that visual short-term memory is capacity-limited in terms of number of objects rather than elements, at around 4 items in size. This was challenged by Wheeler and Treisman (2002), who found that memory for feature binding was worse when recognition memory was tested by re-presenting the whole display again, rather than using a single test probe. They instead claimed that features such as form, color or location are retained in separate stores, and that the bindings between them are reliant on attention to stay intact. While some evidence using concurrent load methodology supports this (e.g. Brown and Brockmole, 2010; Fougny and Marois, 2009), the majority of findings using this and similar approaches indicate that maintenance of bindings, in healthy young adults, is not any more dependent on attention than is the temporary retention of visual information in general (e.g. Delvenne, Cleeremans, and Laloyaux, 2010; Gajewski and Brockmole, 2006; Johnson, Hollingworth, and Luck, 2008; Morey and Bieler, 2013; Yeh, Yang, and Chiu, 2005).

While encoding and maintenance of simple feature bindings may be relatively cost-free in terms of general attentional resources, it is emerging that bound representations are potentially fragile and susceptible to interference caused by subsequently encountered stimuli. For example, when colored shapes are presented serially (as opposed to simultaneously, as in

the research discussed so far), memory for the bindings between these features is disproportionately worse, particularly at early positions in the sequence (Allen et al., 2006; Brown and Brockmole, 2010). In the same way, presenting certain forms of visual ‘suffix’ (i.e. a further item to-be-ignored) during the retention interval can particularly disrupt binding memory (Ueno et al., 2011a, 2011b). Similarly, using a precision-based approach to memory for color and orientation, Gorgoraptis, Catalao, Bays, and Husain (2011) have recently observed an increase in binding errors when items are presented sequentially, specifically caused by disruption of earlier stored representations rather than by temporal decay. This fragility has also been found to be a key factor in whether participants are able to learn shape-color bindings over multiple trials (Logie, Brockmole, and Vandembroucke, 2009). Regarding how information is lost from memory, Cowan, Blume and Saults (in press) have recently suggested that features may be bound in memory (with a capacity limit of only around 3 objects), but these representations can be incomplete; it is possible to retain information about an item’s color, for example, while forgetting its shape (cf. Gajewski and Brockmole, 2006). Thus, when interference and information loss occurs, it does not necessarily proceed in an ‘all-or-none’ manner.

It appears that for healthy young adults, while encoding and retention in visuospatial WM is reliant on central executive control (e.g. Miyake et al., 2001; Morey and Cowan, 2005), simple feature binding is not more so, but it is easily lost from memory. It should be noted however that the majority of research on this topic has examined binding between particularly salient surface features such as color and shape. In addition, a focus has also been placed on the binding of ‘unitized’ features, presented as part of the same object within space. Caution should be exercised when collapsing across different forms of relational and conjunctive processing; we cannot necessarily generalize findings and assumptions to other forms of binding, e.g. between identity and location, between features within the same dimension (e.g. color-color binding), or between features drawn from different objects/locations, all of which may behave differently and draw on different cognitive processes (e.g. Delvenne and Bruyer, 2004; Ecker et al., 2013; Wheeler and Treisman, 2002; Xu, 2002). Nevertheless, recent research has been relatively successful in starting to delineate more clearly how binding may operate in visuospatial working memory. In the same way that we should be aware of how cognitive processes might vary across contexts, it is also important to consider how they may fluctuate across the lifespan.

AGE-RELATED ASSOCIATIVE DEFICITS IN LONG-TERM MEMORY

It has long been known that, in adulthood, episodic memory ability declines in older age. All memorial aspects contributing to episodic memory performance are not, however, uniformly influenced by age. An early meta-analysis by Spencer and Raz (1995) assessed the extent to which aging effects varied with frequently manipulated task demands (for example, recall versus recognition and questions on content versus those on contextual information). Results suggested that memory for content of an episode and memory for the context surrounding and supporting presentation of content are differentially impaired in age comparisons, with memory for context information showing a significantly larger decline

with aging. In reviewing the surrounding literature, Chalfonte and Johnson (1996) considered the existing and varied definitions of 'content' and 'context' information, noting that definitions of the latter range from source information (such as modality or speaker of content) to experimenter defined saliency to information not explicitly instructed for memorization.

The study of context deficits (Spencer and Raz, 1995) and use of a source monitoring framework (Johnson, Hashtroudi and Lindsay, 1993) have been extensively employed in exploring episodic memory. However, Chalfonte and Johnson (1996) focused on characterizing age-related impairment in relation to a question applicable across these approaches: whether older adults are able to maintain individual features within a complex memory (such as item identity, color, location, temporal information, source of presented information) and to maintain associations between these component features. In a series of experiments, older and younger adults were presented with a 7 x 7 grid containing 30 colored, identifiable objects (e.g. telephone, bed, spider) in pseudo-random locations, for a minute and a half, with the instruction to remember one specified feature or feature-feature combination. The same time was then given to consider an instruction consistent test array – that is, consisting of either objects, locations, colors, grid-located items or colored items - with the requirement to identify multiple targets from lures. When instructed to remember location information, older adults' feature memory was impaired relative to that of younger adults, and memory for object-location bindings was also significantly poorer than that of younger adults. In contrast, older adults did not exhibit a feature memory deficit when instructed to remember either color or object identity information, yet an age related binding deficit was observed when tested on the combination of these features. The critical finding of older adults' impairment in memory for color-object identity binding, despite corresponding single feature equivalency with younger adults, was replicated when binding test arrays contained lures created via recombination of non-target features. Previously, lures had been created using one feature from initial presentation (e.g. color) and one novel feature (e.g. a new object) thus this finding, specifically, indicated the binding deficit existed due to poorly formed or retrieved associations between features. Moreover, response methods between feature and association tests were equated in this procedure, employing recognition for both, rather than recognition and recall as has been the case in many episodic, context or source monitoring procedures.

Subsequently, much research has focused on binding difficulties as a means of explaining episodic memory failure in older adults. Naveh-Benjamin (2000) posited the associative deficit hypothesis which suggests that older adults are impaired in their ability to form and retrieve links between 'units' of information – units being defined as items, an item's context, contextual elements or "mental codes" (Naveh-Benjamin, 2000, p 1170) in a broad and encompassing manner akin to that of Chalfonte and Johnson (1996). Importantly, this age-related associative, or binding, deficit is characterized as the existence of a memory deficit for the associated (bound) information, over and above any age-related deficit which may exist for the individual (or unbound) units of information. Naveh-Benjamin revealed the existence of such an associative deficit in older adults when testing recognition of items (words and nonwords) and associations between these items (word-nonword pairs or word-pairs) and also when testing recognition of associations of features presented as one item (word, font of presentation and word-font association). The results of a great deal of studies now indicate an age-related binding deficit in tests of long term memory (see Old and Naveh-Benjamin, 2008a, for a meta-analysis). The deficit has been shown across a variety of stimuli including

word pairs, picture pairs, and face-name pairs (e.g. Naveh-Benjamin, Guez, Kilb, and Reedy, 2004; Naveh-Benjamin, Hussain, Guez and Bar-On, 2003), face-face and face-location pairs (Bastin and Van der Linden, 2005), and for associations between people and their actions (Old and Naveh-Benjamin, 2008b).

Evidence from studies employing numerous materials suggests that older adults do not appear to form associations available under incidental encoding conditions (where associated units are observed at presentation with instruction only to remember single units for visually presented words), even when such associations can prove advantageous. For example, older adults' recognition of words did not benefit from a rich encoding context, while the performance of younger adults was enhanced in a rich compared to a weak visual context (Fernandes and Manios, 2012). Furthermore, Naveh-Benjamin (2000) investigated incidental versus intentional (instructed) encoding of associations and found support for existing results (Chalfonte and Johnson, 1996) indicating that older adults' associative deficit is even greater under intentional learning conditions compared to incidental learning conditions (see also Old and Naveh-Benjamin, 2008a). Recent work has indicated that older adults' associative deficit may in part arise from poor or ineffectual strategy use at encoding or retrieval and that this deficit may be attenuated or eliminated when effective strategies are stimulated (Naveh-Benjamin and Kilb, 2012; Naveh-Benjamin, Brav and Levi, 2007). Such findings provide an interesting avenue for future studies, however it can be noted that a manipulation of full or divided attention reportedly did not interact with age or the variables affecting strategy use (Naveh-Benjamin and Kilb, 2012), as is consistent with previous work indicating divided attention does not differentially affect binding performance of younger and older adults (Kilb and Naveh-Benjamin, 2007, though see Castle and Craik, 2003). This rejection of attentional control as a key contributor to age differences in association formation is somewhat at odds with the claims by Hasher, Zacks, and May (2009) that older adults have particular problems with inhibitory control. Indeed, Campbell, Hasher, and Thomas (2010) have suggested that age-related associative deficits can actually be attributable to 'hyper-binding' in older adults, with reduced inhibitory control leading to formation of extraneous associations in memory, which in turn negatively impinges on goal-relevant binding.

Despite ongoing investigation of underlying causes, the robust evidence for the presence of a specific binding deficit in LTM has prompted recent attempts to establish whether or not such age related associative deficits exist in the working memory domain.

AGING EFFECTS ON VISUOSPATIAL BINDING IN WORKING MEMORY

Mitchell, Johnson, Raye, Mather, and D'Esposito (2000) investigated the influence of aging on visuospatial binding tasks in working memory by employing a similar paradigm to that used by Chalfonte and Johnson (1996). They assessed memory for everyday objects and their locations, which were presented sequentially (i.e., one item at a time) within a 3 x 3 grid. The different forms of memory (object, location, combination) were tested across discrete blocks of trials. The results showed a specific age-related binding deficit, and that this was driven by an increased false alarm rate, that is, difficulty rejecting lure objects that had been created by recombining features presented in the to-be-remembered array. The authors further

showed that the binding deficit was not fully accounted for by the increased test load in the combination trials relative to the individual feature trials. Further work by the same group, using the same paradigm, suggested that impaired hippocampal functioning, and possibly also right prefrontal cortex functioning, underlies the behavioral deficit (Mitchell, Johnson, Raye, and D'Esposito, 2000). The authors concluded that visuospatial binding in working memory might be reliant upon a network in which the prefrontal cortex facilitates hippocampal processing. Indeed, further studies have implicated the hippocampus in visuospatial binding in working memory (Olson, Page, Moore, Chatterjee, and Verfaellie, 2006; Piekema, Kessels, Mars, Petersson, and Fernández, 2006; but see Jeneson and Squire, 2012), though this may depend on the type of binding required; we will return to this later in the chapter.

Cowan, Naveh-Benjamin, Kilb, and Saults (2006) also demonstrated an age-related deficit in memory for colors bound to locations, which was strongest under conditions in which the feature and binding memory trials were mixed within the same block, rather than when trials were presented in discrete blocks according to the form of memory being tested. Cowan et al. also found that the older adults were biased towards responding 'no change', particularly during binding trials. They interpreted this to mean that older adults were relying on familiarity rather than on recollective processes, meaning that they would often overlook the more subtle changes that existed within the array of items when binding memory was being tested. Borg, Leroy, Favre, Laurent, and Thomas-Antérion (2011) also recently demonstrated an age-related deficit for item-location binding. Despite all of this initial evidence of a specific age-related binding deficit in visuospatial working memory, subsequent evidence has been inconsistent. This is because the age-related binding deficit has been fairly elusive when considering the binding of surface visual features such as color and shape, suggesting that the involvement of location as a to-be-remembered feature could be an important factor.

Across three experiments in which both recall and recognition of individual visual features and their combinations was assessed in young and older adults, Brockmole, Parra, Della Sala, and Logie (2008) found that, although older adults exhibited a reliable memory deficit overall, memory for the bindings between these features was not specifically affected by age (see also Parra, Abrahams, Logie, and Della Sala, 2009; and Parra, Abrahams, Fabi, Logie, Luzzi, et al., 2009, for verbal recall of visual material). Furthermore, while Brown and Brockmole (2010) demonstrated an age-related binding deficit in the binding of surface visual features (color and shape), this was in only one of two experiments. In the first experiment working memory for individual colors and shapes, as well as for the combinations, was assessed in young and older adults under conditions of single- (two-digit number repetition) and dual-task (counting backwards in 3s from a two-digit number) conditions. While the results showed a specific binding deficit in attention demanding conditions overall (in contrast to the findings reported by Allen et al., 2006, 2012), there was no specific binding deficit in older adults. In the second experiment the attention manipulation involved comparing simultaneous versus sequential presentation conditions (cf. Allen et al., 2006). As predicted, sequential conditions were disproportionately disruptive for binding memory in both age groups; however, a specific age-related binding deficit was observed overall, independently of the attention manipulation. Age-related binding deficits in specifically visual working memory are therefore observable, but they appear to be unreliable and also quite modest. This conclusion has been supported by recent research we have carried out, in

which a small age-related binding deficit was observed in only one of four experiments (Brown, Niven, Logie, and Allen, 2012).

Variation in methodology more generally may also be contributing to the inconsistency in findings within the working memory domain. For example, using the same paradigm to investigate binding in long- as well as short-term memory, Chen and Naveh-Benjamin (2012) reported that the binding of faces with scenes exhibits a specific age-related deficit in both memory domains. However, in relation to the research investigating visual working memory binding (e.g., Brockmole et al., 2008; Brown and Brockmole, 2010), there are contrasts such as in the active nature of the binding that must be carried out at encoding. That is, Chen and Naveh-Benjamin required extrinsic binding while the other studies involved presenting intrinsically bound objects. The stimuli themselves were also more complex, albeit perhaps more ecologically valid (i.e. faces and scenes rather than basic colors and shapes). Furthermore, a continuous recognition paradigm was used by Chen and Naveh-Benjamin, in which items presented for study and test are intermixed, rather than presenting distinct trials featuring ordered study and test phases. This may be important, particularly as research has shown the fragility of bindings in working memory and the relative ease with which they may be overwritten by subsequent information (Allen et al., 2006; Brown and Brockmole, 2010; Ueno et al., 2011a).

One apparent consistency within the literature on visuospatial binding in working memory is that limited attentional capacity in older adults does not appear either to fully account for (Cowan et al., 2006) or bring about (Brown and Brockmole, 2010) the deficits. This may relate to the argument that the hippocampus is the key relational processor required for binding. Thus, rather than an attention deficit, an impairment in associative processing or memory per se may underlie age-related visuospatial binding deficits in working memory, where they do exist.

VISUOSPATIAL BINDING IN WORKING MEMORY IN ALZHEIMER'S DISEASE

In contrast to the inconsistent findings within the literature on healthy aging, a marked, reliable working memory binding deficit has been observed in AD patients. For example, Parra, Abrahams, Fabi, Logie, Luzzi, et al. (2009) compared working memory for color-shape bindings, verbally recalled, in AD patients with that of healthy, age- and education-matched control participants. Importantly, effects of overall memory capacity were controlled by calibrating the number of to-be-remembered items across the two participant groups, to the point where performance for individual feature memory was equivalent. The authors found that, in the AD patients only, binding performance was poorer than individual feature memory, concluding that AD markedly and specifically affects mechanisms responsible for binding features in working memory (see also Borg et al., 2011; Parra, Abrahams, Logie, and Della Sala, 2010; Parra, Abrahams, Logie, Méndez, Lopera, et al., 2010). Parra, Della Sala, Abrahams, Logie, Méndez, et al. (2011) further showed that a specific binding impairment is also present in AD patients in within-dimension (color-color) binding, and concluded that, rather than relying specifically upon the hippocampus, working memory binding may depend upon surrounding cortices (i.e. perirhinal and entorhinal cortex) that is known to degenerate

with AD. Remarkably, Della Sala et al. (2010) demonstrated that specifically AD, and not any of a number of non-AD forms of dementia, is sensitive to working memory binding deficits. They argued that this supports the claim that extrahippocampal regions are critical to working memory binding, due to the earlier and more severe effects seen in these areas with AD as compared with non-AD dementias.

How might this relate to other research indicating a role for the hippocampus in certain forms of age-related binding deficit, and to evidence on WM binding and the hippocampus in general? As already noted, an important distinction might exist between intrinsic and extrinsic, or conjunctive and relational, binding (e.g. Ecker et al., 2013; Moses and Ryan, 2006). It is possible that, for both working memory and LTM, the hippocampus might have a particular role in building and retaining extrinsic or relational bindings, that is, between elements from different objects or parts of an object, and binding to location and other contextual information (Ecker et al., 2013, but see Jeneson and Squire, 2012). In these cases, older adults may show impairment at least partly as a result of hippocampal degradation associated with healthy aging (West, 1993). In contrast, intrinsic or conjunctive binding (between elements that are unitized as part of the same object) may operate independently of the hippocampus, at least for WM. For example, Baddeley, Allen, and Vargha-Khadem (2010) observed intact visual WM for the binding of shape and color in Jon, a patient with developmental amnesia resulting from highly selective hippocampal damage. Thus, WM binding deficits in aging may be attributable to PFC and hippocampal loss connected to extrinsic binding, while further impairment shown by AD patients in intrinsic binding may reflect involvement of and damage to extrahippocampal areas (which are relatively unaffected by cognitive aging). Somewhat in line with this, Parra and colleagues (Parra, Cubelli, and Della Sala, 2011; Parra, Della Sala, Logie and Abrahams, 2009) have reported a case study of an individual with damage to the anterior pole of the left medial temporal lobe, who demonstrated impaired 'intrinsic' shape-color binding in visual WM, alongside intact binding between colors (analogous to extrinsic, or relational binding). This possible intrinsic-extrinsic distinction may cut across WM and LTM, in terms of aging deficits and of the involvement of the hippocampus (though Jeneson and Squire, 2012, have recently argued against any medial temporal lobe contribution to WM). Alternatively, such a distinction may be a key factor only in WM, with any form of binding showing an age-related impairment in long-term memory tasks.

FUTURE DIRECTIONS

As indicated by the research described so far, it remains to be seen to what extent different forms of information binding are consistently intact or impaired as a result of the healthy aging process. Certainly in terms of binding and association formation in LTM, older adults appear to demonstrate reliable deficits relative to individual element retention, and to young adults. Within WM however, this may vary to a greater extent, possibly depending on the type of stimulus and conjunction involved. It is important that future research attempts to address more precisely the boundary conditions at which older adults consistently show intact or impaired performance. As current work might indicate (e.g. Brown et al., 2013), this is not necessarily a straightforward process, as it is possible to observe occasional but inconsistent

patterns of impairment in older participants. Nevertheless, identifying the conditions under which reliable deficits emerge remains a viable aim. Thus, examination of factors such as within- vs. cross-modality binding, unitization, and the intrinsic-extrinsic distinction already discussed, would be potentially fruitful directions to pursue in future. Examining how different aspects of WM and attention might be involved in age-related binding deficits would be of value, as different sub-components may be variably affected by cognitive aging (e.g. Craik, Morris, and Gick, 1990; Reuter-Lorenz and Jonides, 2008). Similarly, exploring the interface between WM and LTM in this context would be useful, in order to potentially identify over what timeframes binding deficits become more problematic with age, and how different performance patterns over the short- and long-term can be reconciled. Finally, a greater consideration of the role of strategic processing would be important; the extent to which older adults are able to implement strategies to support memorial performance, and how this relates to any patterns of impairment that are observed, may help clarify when binding itself is genuinely and reliably impaired, and when this is a result of either more general deficits in strategy-use, or idiosyncratic strategy use obscuring real deficits.

CONCLUSION

Recent developments have begun to elucidate how feature binding might operate, with implications for the possible structure of working memory, interactions with attention, and what determines information loss over short delays and in the face of interference. Different cognitive processes and brain regions might contribute to binding, depending on factors such as the nature of the constituent features and the binding that is required, their relative spatial configurations, and the type of memory task involved. This may be important in determining whether binding declines as a function of cognitive aging. A number of studies have observed such a decline, while others have failed to observe particular binding deficits above and beyond any problems with memory for individual features. It is important that subsequent research attempts to clearly delineate the conditions that consistently give rise to age-related binding deficits. While it remains a challenge to draw this out amid the greater inconsistency and variability often associated with older adults' performance, doing so will not only aid understanding of the cognitive aging process, but also of disorders such as Alzheimer's disease.

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