Investigating Visual Working Memory

On how Task-Demands Differentially Influence Processing of Intrinsic and Extrinsic Object Information

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CONTENTS

LIST OF PAPERS

Part of this work is included in published and submitted articles. Experiment 1 was published as Kirmsse, Zimmer, and Ecker (2018) in the Journal of Psychology and Aging. Data from Experiment 4 is prepared for submission as Kirmsse, Zimmer, and Ecker (in preparation). For both articles, I am the first author.

Kirmsse, A., Zimmer, H. D., & Ecker, U. K. H. (2018). Age-related changes in working memory: Age affects relational but not conjunctive feature binding. *Psychology and Aging*, *33*(3), 512–526. https://doi.org/10.1037/pag0000249

Kirmsse, A. & Zimmer, H. D., Ecker, U. K. H. (in preparation). Task demands differentially affect processing of intrinsic and extrinsic object features: Electrophysiological evidence for an intrinsic processing advantage.

In order to guarantee a smooth reading experience, the corresponding passages are not marked in the text. Further, in keeping with the practice of these articles, in the main text I consistently employ “we” instead of “I”.

LIST OF ABBREVIATIONS

°	Degree
%	Percent
€	Euro
ACC	Accuracy
ANOVA	Analysis of variance
CDA	Contralateral delay activity
cf.	confer, compare
CI	Confidence interval
CNSW	Contralateral negative slow wave
CNV	Contingent negative variation
e.g.	exempli gratia, for example
ERP	Event-related potential
et al.	et alteri, and others
F	Test statistic from F distribution
fMRI	Functional magnetic resonance imaging
Hz	Hertz
i.e.	id est, that is
IPS	Intraparietal sulcus
kΩ	Kiloohm
LTM	Long-term memory
M	Mean
ms	Milliseconds
p	Probability of equally extreme test statistic, given null hypothesis is true
r	Pearson product-moment correlation coefficient
RGB	Red, green, and blue, system for representing colors
ROI	Region of interest
RT	Response time
SD	Standard deviation
SE	Standard error
SOA	Stimulus onset asynchrony
SPCN	Sustained posterior contralateral negativity
t	Test statistic from Student's t distribution
WM	Working memory
η_p^2	Effect size for ANOVAs with repeated measurements (partial eta squared)
µV	Microvolt

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ABSTRACT

The visual working memory (WM) serves to hold a limited amount of information available to human cognition. This allows for further manipulations even if the information is no longer available in the physical environment. The properties of visual WM are often investigated by change detection tasks, where participants are required to store a controlled amount of information. After a short retention interval, during which the information is no longer available, participants are asked to compare new presented information with what they maintained in WM. Participants then indicate whether the new information is the same or changed to the stored memoranda. Some models of WM assume that the units represented are integrated objects. In the physical environment, however, visual units consist of numerous features and parts. Studies revealed that the visual WM is influenced by how information is distributed across the visual object with some information being more likely to be integrated in a WM representation than other. The goal of this dissertation project was to investigate whether binding mechanisms influence process. Based on findings from long-term memory (LTM) research within the framework of the type-token model (Zimmer & Ecker, 2010), we assumed that if objects consist of multiple features, intrinsic surface features of objects should be *obligatorily* integrated into a WM representation while extrinsic object features that are no inherent part of the objects outline have to be *intentionally* bound to the WM representation. Moreover, the binding of extrinsic object information was expected to be a *supplementary* process to intrinsic binding, as extrinsic binding refers to the mechanism of associating individual visual entities. Further, while intrinsic binding was assumed to be mediated via perirhinal structures, extrinsic binding was assumed to rely on the intact functioning of the hippocampus. In a series of four experiments, we found that the visual WM does not operate with integrated objects under all conditions. Our results indicate that intrinsic but not extrinsic object information is unintentionally represented in WM. In contrast to findings from LTM, in WM this effect was unlikely the result of different binding mechanisms mediated via the hippocampus. We argue that scaling the focus of attention based on the visual properties of the memoranda could be of critical importance for the benefit of intrinsic over extrinsic features.

Our first goal was to investigate, whether intrinsic and extrinsic binding mechanisms rely on the intact functioning of different neural structures. Critically, the hippocampus is considered one of the first brain regions to be affected by age-related degenerative changes. In Experiment 1, we contrasted the short-term retention of shape-color associations using a change-detection task with colors and shapes in younger and older

healthy adults. In a direct test of associative memory, participants were required to memorize the exact shape-color associations; in an indirect item memory test, participants were required to memorize only the shapes. To investigate the unintentional processing of information, we examined the costs of ignoring task-irrelevant color changes from study to test. In the direct test, associative memory was poorer when extrinsic binding was required rather than intrinsic binding, and associative memory was poorer in the older group, but no age-related association deficit was apparent. In the indirect test, by contrast, type of binding interacted with age: younger participants showed study-test congruence effects independent of the type of binding, but older adults showed enhanced congruence effects for intrinsic stimuli, indicating intact intrinsic binding, and virtually no costs for extrinsic stimuli, indicating poor extrinsic binding. This stimulus-specific effect of a task-irrelevant feature change indicates that extrinsic and intrinsic binding in WM are differently affected by healthy aging. This, however, was most likely not the consequence of an impaired binding process for extrinsic associations arising with age.

In Experiment 2, we manipulated the presentation time of the to-be-remembered intrinsic and extrinsic feature associations. If extrinsic binding represents a mechanism downstream to intrinsic binding, we would assume that extrinsic binding is more time dependent than intrinsic binding. We found no indications that binding of intrinsic and extrinsic shape-color associations were differentially affected by the time available to consolidate the information into a WM representation. This was found for older and younger adults. Instead, an observed age-related decrease in extrinsic binding performance was most likely caused by a general decrease in extrinsic feature processing.

From Experiments 1 and 2, we concluded that the increased processing demands for extrinsic information are unlikely the result of the binding process. Instead, the transfer of extrinsic features into WM seems to place higher demands on the WM itself. The goal of Experiment 3 was to investigate whether intrinsic and extrinsic associations place different demands on the short-term retention of the corresponding information. Using a bilateral version of the change detection task, we evaluated the contralateral delay activity (CDA) during the maintenance phase after the information was transferred to WM. This slow wave potential is assumed to reflect the neurophysiological correlate of storage demands in WM. Mean amplitudes of the CDA did not differ for intrinsic and extrinsic shape-color associations. We suggest that, once transferred into a stable representation, intrinsic as well as extrinsic stimuli can be retained as an integrated unit.

Experiments 1 and 2 yielded that intrinsic information is involuntarily part of the representation that is used to evaluate the test probe. This interpretation is based on behavioral recognition performance, reflecting the final result of a process chain. Experiment 4 was set out to investigate whether early neurophysiological signals related to mismatch detection (frontal N2) can substantiate the distinction between involuntarily represented intrinsic and rather intentionally represented extrinsic information. We contrasted WM performance in a direct test where participants intentionally stored color-shape associations and in an indirect test where participants had to retain only shape but not color information. In the critical condition, intrinsic or extrinsic color information was changed from study to test. In the direct test, electrophysiological activity locked to the onset of the test stimulus indicated that changes to both intrinsic and extrinsic color features elicit early event-related potentials associated with mismatch detection. In contrast, in the indirect test condition, changes to intrinsic but not extrinsic features elicited a mismatch signal. Furthermore, the amplitude strength of the intrinsic mismatch N2 was found to influence later processes of target evaluation (as reflected by changes in the latency of a P3-like positive component), possibly contributing to a more unequivocal decision finding process.

The results obtained in the present dissertation project replicate previous findings of a processing advantage of intrinsic over extrinsic information. We contribute to existing knowledge by demonstrating that this processing advantage is most likely not the result of different binding mechanisms, as it, for example, found for LTM performance (Zimmer & Ecker, 2010). Instead, we argue that the distribution of visual information differentially affects the scaling of the attentional focus. As a consequence, object-inherent intrinsic but not extrinsic information gains a processing advantage, increasing the likelihood that this information is integrated in a WM representation. We interpret these findings in terms of a WM model suggested by Cowan, Blume, and Saults (2013): the visual WM capacity is limited to a specific amount of objects, but these object representations can be incomplete depending on the direction of attention.

1 INVESTIGATING VISUAL WORKING MEMORY

In our everyday life, we do not constantly re-orient ourselves every moment we experience. We perceive our environment as permanent and coherent. Our working memory (WM) allows us to temporarily represent a limited amount information from varying domains (e.g., visual, auditory, spatial) in order to allow further processing to monitor or guide our behavior, even if the information itself is physically no longer available (e.g., Baddeley, 2012; Cowan et al., 2005). WM is, hence, a fundamental component of human cognition, at the "*interface between perception, long-term memory and action*" (Baddeley, 2003, p. 829). Variations in WM performance influence a broad range of cognitive aptitudes, such as planning, problem solving, reading comprehension, decision making, abstraction, or fluid intelligence (see, e.g., Conway, Jarrold, Kane, Miyake, & Towse, 2007; Engle, Tuholski, Laughlin, & Conway, 1999; Unsworth, Fukuda, Awh, & Vogel, 2014). WM is a neuro-cognitive system that allows us to react to current circumstances or changes (e.g., Zimmer, 2008) and its properties are of major importance for task-relevant functioning.

A significant number of research projects have been devoted to the investigation of visual WM. One of the most central properties of the visual WM is its highly limited capacity of a maximum of approximately three to four information units. If the amount of information exceeds this limit, WM performance significantly decreases (e.g., Cowan, 2001; Luck & Vogel, 1997; Raffone & Wolters, 2001; Vogel, Woodman, & Luck, 2001). Such capacity limitations have been found to be stable within individuals (e.g., Xu, Adam, Fang, & Vogel, 2018).

How information from the visual environment is transferred to and represented in WM is one of the most debated questions in the field of research. Despite the narrow limits of visual WM capacity, a closer examination reveals surprising differences in the integration of features into visual WM representations: On the one hand, some models suggest that the visual WM operates with representations of whole objects, with all object features being integrated—that is, *bound*—into each object representation. For example, two features that stem from the same object are remembered just as well as a single feature from this object (see Luck & Vogel, 2013, for a review). Other studies cast doubts on the assumption that the visual WM operates with integrated objects. Fougnie and Alvarez (2011) found, that participants can retrieve some features of a multi-featured object, while other features are forgotten. For example, participants can still remember the color of an object, whilst they cannot recall any information about the object's shape. Similarly, Fougnie, Asplund, and Marois (2010) found, that remembering more features per object influences the precision of the corresponding representation. Moreover, adding features to the representation that were not inherent to the object’s outline influences the precision but also the probability that the features will be represented at all. These findings indicate that storing information in WM is most likely not a unitary process and WM performance is influenced by the distribution of features across the object.

Ecker, Maybery, and Zimmer (2013) suggest that at least two different *binding* mechanisms significantly influence the integration of information into WM representations. Originating from long-term memory (LTM) research (e.g., Zimmer & Ecker, 2010), Ecker and colleagues draw a distinction between *intrinsic* and *extrinsic* binding (Ecker, Zimmer, & Groh-Bordin, 2007a, 2007b; Ecker, Zimmer, Groh-Bordin, & Mecklinger, 2007). Intrinsic binding is considered a rather automatic or cost-free process that binds information inherent to the contour of the object itself, for example storing the information that the triangle was presented in red color (O'Craven, Downing, & Kanwisher, 1999). Extrinsic feature binding, however, is argued to be a more deliberate process that associates independent perceptual units in perception and memory, for example, an object and the context it appeared in (Cabeza, 2006). Intrinsic feature binding could thus be a byproduct of the perceptual encoding process, whereas extrinsic binding could be a supplementary process that is only executed if the task context demands it (Zimmer & Ecker, 2010).

In contrast to LTM, the type of binding required has seldom been considered to influence WM performance (e.g., Ecker et al., 2013; Fougnie et al., 2010). The present dissertation project is set out contribute to a better understanding of the influence of the type of binding on WM functioning: Are intrinsic bindings automatically formed in WM? Do extrinsic bindings represent a supplementary WM process that is intentionally engaged? Do they rely on different neural structures? And can we assume that comparable binding mechanisms influence LTM and WM?

Within the next chapters, we will, first, elaborate on our concept of WM and how information about the processes that contribute to measurable WM performance can be obtained, behaviorally and on a neurophysiological level. We will, second, discuss “what” might be represented during WM tasks, as data about the nature of the WM representation is far from being conclusive. Third, we will introduce a theoretical model that provides a framework that might contribute to our understanding why some information is retained in WM without any ease while other is not.

1.1 CONCEPTION OF WORKING MEMORY

Multiple theories exist that influenced the investigation of WM functioning (for an overview, see Miyake & Shah, 1999a). Despite large conceptual differences and a great variety of scientific approaches (e.g., Baddeley & Hitch, 1974; Cowan, 1995; Engle et al., 1999), one commonality among most approaches is that maintaining a limited amount of (task-relevant) information accessible for further tasks is a key determinant for WM (Miyake & Shah, 1999b).

In the 1970s, Baddeley and Hitch (1974) introduced their tripartite model of WM. It conceptualizes WM as a specialized cognitive entity with three components: one system responsible for the allocation of attention, labeled the central executive, and two subordinated storage systems, the phonological loop for verbal or phonological content, and the visuospatial sketchpad for visual and spatial information. Both storage systems represent capacity-limited and modality-specific buffers that operate independently from each other. Information in one storage system does thus not interfere with information in the other when operating in parallel. The central executive represents a capacity-limited instance that regulates the allocation and division of attentional resources to the phonological loop and visuo-spatial sketchpad. It switches the engagement between tasks and is assumed to provide an interface for LTM contents to influence WM functioning. Later, the capacity-limited episodic buffer was introduced as a fourth component "*that allows features from different sources to be bound into chunks or episodes*" (Baddeley, 2012, p. 16). The episodic buffer is thought to subserve the integration of perception and LTM with WM, whilst relying on attentional resources provided by the central executive (Baddeley, 2000).

Understanding WM as a system of centrally controlled separate buffers leaves some important questions. For example, it is debatable which components contribute to the differences in WM performance for information of different visual patterns. Moreover, it is still under debate, whether the division of WM into the illustrated components is sufficient. While some researchers argue in favor of a more fine-grained subdivision of the visuospatial sketchpad into stores for passive-visual material and dynamic-spatial information (Logie, 1995), other studies provided results against further subdivision (e.g., Zimmer & Lehnert, 2006). The exact constraints to these findings are yet to be explored (see Allen, 2015; Baddeley, 2012) and go way beyond the scope of the present thesis.

Other theories adopt a more functional conceptualization, where WM is not considered a separate entity or a specialized buffer. Instead, the concept of "working memory" refers to the entirety of mnemonic functions that keep information in a state that it can be used to encode, maintain and retrieve information to solve tasks with mental components (Cowan, 1999, 2016). In his embedded process model, Nelson Cowan (1988, 1995) considered information currently held in WM as information in an accessible state of heightened activation (sometimes argued in the sense of activated cell assemblies, e.g., by Hebb, 1949). Other than Baddeley and Hitch (1974), Cowan (1988, 1995) did not assume that the WM is arranged in a modality-specific manner. Instead, information that enters WM is based on different faculties: a) information that is stored in LTM, b) a subset of information from LTM that is currently activated, and c) the subset of activated memory information that is in the current focus of attention and awareness. Moreover, although activated information does not necessarily enter the focus of attention, it is in a more accessible state. This raises the likelihood that the information can be retrieved or can influence mental processes. A central executive process controls the distribution of the focus of attention. This attentional control process can be influenced by task demands, which can result in increased activation or inhibition of information. As information in WM and LTM differ in terms of activation, they do not necessarily demand for existence of distinct WM and LTM systems.

Neurocognitive models describe WM as an "*emergent property*" (Postle, 2006, p. 29) of all neural processes involved in maintaining the representation of information when the corresponding information is no longer available in the environment. Put differently, "*the retention of information in working memory is associated with sustained activity in the same brain regions that are responsible for the representation of that information in non-working memory situations [...] [and humans] recruit as many mental codes as are afforded by a stimulus when representing that stimulus in working memory*" (Postle, 2006, p. 31). Information can thus be represented on different levels of abstraction. Representations activate adequate networks as long as the representations are needed for the task. If the task is finalized, the activation subsides. Since each representation leaves behind traces of activation patterns, such representations are easier to (re-)address (Zimmer, 2008).

In the present thesis, we do not conceptualize WM as an isolated entity that provides space for representing information. Instead, we obtain the position that WM emerges as a property from the required cognitive processes and the associated patterns of activation of neural structures. Therefore, we do not assume that WM functions in isolation, but can be influenced by perceptual or LTM processes (Cowan, 1988, 1995; Postle, 2006; Zimmer, 2008). The present research project is set out to contribute to the understanding of the cognitive processes related to encoding, maintaining, and retrieving information while performing a task that requires the short-term retention of visual information. In the following, we will introduce a paradigm that is frequently used to investigate visual WM performance, as well as neurophysiological correlates of WM functioning.

1.2 MEASURING VISUAL WM

One hallmark property of WM is its strict limitation (e.g., Brady, Konkle, & Alvarez, 2011; Conway et al., 2007; Cowan, 2016). However, when investigating visual WM, we are not only investigating "limits". Rather, we are investigating the performance in a complete task that involves multiple processes that contribute to these limits. WM tasks typically require an observer to encode and retain a specific amount of information for a circumscribed amount of time during which the information is no longer available. Afterward, the observer has to compare the retained information with a probe and is required to indicate whether any information was altered. Thus, in the initial encoding phase, the observer, first, has to transform the fleeting perceptual impression of the to-be-retained information into a stable WM representation (Vogel, Woodman, & Luck, 2006). Second, the stored representations have to be kept persistent and protected from degradation and interference after the to-be-retained information has been removed from the environment. Third, the represented information has to be compared against the incoming stream of new visual information (see Gazzaley & Nobre, 2012, or Luck, 2008, for overviews). A decision rule has to be applied to decide whether the new information deviates from the studied information (e.g., Cowan, Blume, & Saults, 2013; Hyun, Woodman, Vogel, Hollingworth, & Luck, 2009). The behavioral response given by a subject only reflects the final result of all processes that take place during the task.

1.2.1 THE CHANGE DETECTION TASK

As a WM representation cannot be measured straightforwardly, the paradigm of the change detection task has proven to be a paramount tool to help to elucidate the properties of the representation, while minimally influencing the nature of the representations themselves (for an overview, see, e.g., Rensink, 2002). During a change detection task, participants typically see an array of a specific number of visual stimuli (e.g., colored shapes) for usually a few hundred milliseconds. Participants are instructed to memorize the stimuli. After a short delay of commonly one second—during which the memoranda are no longer visible—a second array is presented that is same or different to the initially presented array. Participants then have to indicate whether they detect a change or whether they consider the second array to be same to the first one (e.g., Luck & Vogel, 1997). Response accuracy or response time (RT) are common variables to gain knowledge about influences on change detection performance. Thus, although the change detection task is an artificial situation that only approximates everyday life, it "*closely resembles the way in which [visual WM] is used in the natural environment*" (Luck, 2008, p. 47).

The change detection task has several virtues: its relatively simple trial structure makes it easy for the participant to understand, and—in addition to young adults—the task can be performed by children as well as older people (e.g., Sander, Lindenberger, & Werkle-Bergner, 2012). Potential influences of sensory limitations can be minimized by the use of appropriate stimuli, for example by utilizing easy to encode material or adequate presentation times (e.g., Naveh-Benjamin & Kilb, 2014). Influences on response systems can be adapted by simple two-alternative forced-choice responses that can also accommodate age-related concerns of contact with newer computer technology by providing specialized response keyboards. Single probes can be presented to reduce interference at the time of test (e.g., Wheeler & Treisman, 2002). As a consequence, processes that are "*nonmemory*" (Luck, 2008, p. 47) in nature can be minimized to increase the change detection task's sensitivity to the visual WM system.

Furthermore, the trial structure of the change detection task can be modified to accommodate the given research question. Systematic variations to the number of the to-be-remembered items can help to clarify capacity limitations in WM (e.g., Luck & Vogel, 1997). Varying the visual format of the memoranda can be used to increase our understanding of the nature of the visual WM representation (e.g., Fougnie et al., 2010). By presenting masks that terminate influences of sensory memory, it is possible to closely follow the process of transferring visual input into stable WM representations (e.g., Vogel et al., 2006). Presenting distracting or task-irrelevant information along with the relevant stimuli makes the investigation of selection mechanisms possible (e.g., Gao, Ding, Yang, Liang, & Shui, 2013). The adaptive structure of the task contributes to the collection of findings that can be compared across different studies.

Besides its advantages, it is still necessary to investigate obtained change detection data with the appropriate caution. Although it is a visual task, performance could be affected by other processes unrelated to visual WM. The possibility that visual information can also be encoded in a linguistic way is an open question in this issue. For example, observers could mentally rehearse the words of the colors (e.g., "red, blue, green, red, blue, green, red…") instead of visually maintaining the represented color pattern throughout the maintenance phase. The influence of verbalization processes can be reduced, for example, by using abstract or difficult to name stimuli (e.g., Attneave & Arnoult, 1956), by requiring participants to perform a concurrent verbal task to block verbal rehearsal strategies (e.g., Vogel et al., 2001), or short retention intervals that do not allow for sophisticated verbal rehearsal (e.g., Luck & Vogel, 1997). It is, however, important to note that visual WM performance appears to be largely unimpaired by easy-to-perform concurring verbal tasks (e.g., Allen, Baddeley, & Hitch, 2006; Luck & Vogel, 1997; Treisman & Zhang, 2006), suggesting that verbal processes do not compete with visual WM processes for some form of common resource. Xu et al. (2018) argued, that the change detection task is found to produce intra-individually reliable data across time. In sum, visual change detection tasks represent an instrument well suited to investigate the short-term retention of visual information.

1.2.2 ELECTROPHYSIOLOGICAL CORRELATES ASSOCIATED TO WM PROCESSES

Behavioral measures represent the end result of a series of processes taking place to solve a change detection task. The final end result may be biased by decision-making processes (see, e.g., Fitousi, 2018, for a comparable discussion) or strategic effects (e.g., Peterson & Naveh-Benjamin, 2016). Neurophysiological methods, such as recordings of electro-physiological potentials at the scalp, contributed to a better understanding of the individual processes that determine the final performance and are less prone to bias. Two neurophysiological correlates are of specific interest for the present thesis: first, the contralateral delay activity, that is argued to reflect the cognitive effort needed to retain information; and second, the N2, that is found to indicate the processing of a mismatch between retained and incoming information.

1.2.2.1 The Contralateral Delay Activity

With respect to the retention of information in visual WM, a large body of research has focused on slow waves appearing during the maintenance phase after the study array offset. Ruchkin, Johnson, Canoune, and Ritter (1990) demonstrated that the retention of visual information in a WM task is accompanied by a sustaining positive wave. At this point, it was unclear how other non-mnemonic processes, such as response preparation, anticipation or arousal (e.g., McCollough, Machizawa, & Vogel, 2007), contributed to the development of the slow wave (see Luria, Balaban, Awh, & Vogel, 2016, for a similar discussion). In subsequent studies, it has been shown that the amplitude of the slow waves appearing during the retention of information is strongly associated to the amount of task-relevant information retained in WM (e.g., Arend & Zimmer, 2011; Mecklinger & Pfeifer, 1996). Positive slow waves thus remained a promising target to investigate functions associated with WM (García-Larrea & Cézanne-Bert, 1998).

One method to overcome potentially obscuring variables such as arousal or anticipation is based on a bilateral adaption of the change detection task (see *Figure 14* for an example): Balanced information is presented to the left and right hemifield of the human vision. Based on the work of Klaver, Talsma, Wijers, Heinze, and Mulder (1999), Vogel and Machizawa (2004) made use of the contralateral hemispheric organization of the human visual system to exclude brain activity that is non-specific to the memoranda. Participants were instructed to remain fixed with their gaze to a cross in the middle of a screen where the task information was presented. Most important, task-relevant stimuli were shown left and right to the fixation cross, but participants had to retain only one side of the display, for example, only the stimuli presented to the left of the fixation cross. According to the organization of receptive fields in the human brain, information from the left visual hemifield is processed in the contralateral brain hemisphere and vice versa. Task-general processes not specific to the attended (hemispheric) information should influence neurophysiological processes in both brain hemispheres. Thus, task-unspecific neural activity should be minimized if neural activities from the attended and unattended visual hemisphere are compared. This can be achieved by subtracting the recorded activity from the brain hemisphere ipsilateral to the attended hemifield from the activity contralateral to the attended hemi-field (e.g., Luria et al., 2016). The remaining negative event-related potentials (ERPs) are argued to reflect activity associated with WM maintenance of the attended memoranda. In WM research, the resulting ERP is often referred to as the contralateral delay activity (CDA; e.g., Jost, Bryck, Vogel, & Mayr, 2011; Vogel & Machizawa, 2004; Vogel, McCollough, & Machizawa, 2005). However, during the last years, comparable activity was observed under other conditions not uniquely tied to WM maintenance, resulting in slightly varying nomenclature, such as the SPCN (sustained posterior contralateral negativity; e.g., Jolicœur, Brisson, & Robitaille, 2008), or the CNSW (contralateral negative slow wave; Klaver et al., 1999).

Applying the logic of hemispheric information processing, Vogel and Machizawa (2004) found that the CDA varies with the amount of information retained in WM during the maintenance phase. The authors let participants study varying numbers of color patches in a bilateral version of the change detection task, while the participants' electrophysiological signal was recorded. After calculating the corresponding difference wave, Vogel and Machizawa (2004) observed a negative-ongoing slow wave most prominent over posterior parietal and lateral occipital electrode sites. This CDA varied as a function of the set size but plateaued as soon as the participant's individual WM capacity limit was reached. That is, if a participant had an individual WM capacity limit of three color patches, the CDA progressively increased from set size one to three, while the CDA for set sizes three and four were not significantly different. Similarly, Vogel et al. (2005) found that individuals with high WM capacity show larger increases in CDA amplitudes compared to individuals with lower WM capacity. The CDA component could be replicated for simple and complex objects (e.g., Luria, Sessa, Gotler, Jolicœur, & Dell'Acqua, 2010; Luria & Vogel, 2011; Quak, Langford, London, & Talsma, 2018).

Corroborating the interpretation that the CDA reflects the amount of information currently held in WM, the CDA is not found to be influenced by basic perceptual factors such as high or low contrast stimuli (Ikkai, McCollough, & Vogel, 2010; Luria et al., 2010). In addition, the CDA does not reflect the number of attended locations, as the sequential presentation of the memoranda on the same location lead to similar CDA waveforms compared to presentation on distinct locations (Ikkai et al., 2010). Additionally, varying the spatial relations between to-be-remembered objects does not modulate the CDA (McCollough et al., 2007). This is underpinned by studies showing that different stimuli that share the same location are not inevitably integrated into one object (Balaban & Luria, 2016; Luria & Vogel, 2014). Furthermore, the CDA might not reflect other non-mnemonic factors such as task-difficulty. Besides an increase in the number of objects, task-difficulty ascends with set size: an increasing number of stimuli have to be distinguished. However, the CDA plateaus at the same level as the WM capacity limit (e.g., Vogel et al., 2005). This suggests that the influence of task-difficulty is only of minor importance for the CDA. In addition, the amplitude of the CDA appears to be more pronounced for correctly solved trials compared to incorrect trials (e.g., Experiment 3 from McCollough et al., 2007). The reported findings strengthen the assumption that the number of objects currently retained in WM is the major influence for the amplitude of the CDA (see Luria et al., 2016, for a meta-analysis).

Whereas the reported studies speak in favor of the CDA representing a finite number of objects held in VWM, there is also evidence that the CDA is influenced by informational load, as indexed as the visual appearance of the to-be-remembered stimuli. Luria et al. (2010) systematically varied the informational load by changing the complexity of the objects' outlines. The authors found the amplitude of the CDA to be increased when participants retained two complex random shapes as when they had to retain two simple color patches. As the set size was rather low in this study, this effect was unlikely influenced by participants reaching their WM capacity limit. Luria and Vogel (2011) found that the amplitude of the CDA enhanced if the same number of complex random shapes compared to simple color patches had to be retained. However, adding color information to complex shapes did not increase the CDA any further. Tearing apart simple and complex features of objects by changing the visual presentation via reducing high spatial frequencies of complex objects, Gao et al. (2013) reported further evidence that the informational load influences the characteristics of the CDA: whereas the CDA did not increase from set size two to set size four for clearly visible complex shapes, a significant difference was found when the set size was increased for blurred complex shapes that only revealed simple visual information (see Experiment 3 from Gao et al., 2013). Hence, to some extent, the CDA does reflect storage demands during WM tasks.

To conclude, there is convincing evidence that the CDA represents the number of objects successfully held in VWM, while it is unaffected by boundary conditions such as contrast, spatial distribution or number of locations. However, the CDA is to some extent influenced by the visual properties of the material. As the present thesis focusses on the maintenance of different types of visual information, in Experiment 3 the CDA is utilized as a measure for the storage demands of intrinsic and extrinsic stimuli during the maintenance phase.

1.2.2.2 The N2

ERPs locked to the onset of the test stimulus can contribute to our understanding of the representation available used to evaluate the probe. To indicate whether the test probe is same or changed, a comparison between the information retained in WM and the new incoming information is needed. A neural correlate that is discussed to track this process is the frontal N2.

The frontal N2 (or sometimes also referred to as N2b; e.g., Luck, 2014) is characterized as the second negative deflection in the averaged ERP waveform. It is found most prominent over frontal electrodes 200 ms after stimulus onset (see Folstein & van Petten, 2008, for an extensive review). Initially, the N2 was described in the two-stimulus oddball paradigm, where participants monitor a series of identical stimuli, interrupted by rare deviating stimuli that required a specific response. When comparing the rare to frequent stimuli, responses rare stimuli evoke a larger N2 (for an overview, see Folstein & van Petten, 2008). More general, the N2 is found to vary with the processing of a conflict signal that arises from deviating attributes of a new incoming information from a mental template currently held active in WM (Folstein & van Petten, 2008; Wang, Cui, Wang, Tian, & Zhang, 2004; Yin et al., 2011). For example, in the Eriksen flanker task, a larger N2 is observed for trials with task-incongruent distractors than for congruent trials (e.g., Gehring, Gratton, Coles, & Donchin, 1992; Yeung, Botvinick, & Cohen, 2004). Similar results were obtained for incompatible compared to compatible trials in the Stroop task (Liotti, Woldorff, Perez, & Mayberg, 2000; West & Alain, 1999).

The N2 can be elicited by various stimulus manipulations, such as deviating colors (Gao, Li, Yin, & Shen, 2010; Tian, Wang, & Wang, 2001), shapes (Cui, Wang, Wang, Tian, & Kong, 2000; Gao et al., 2010), or numbers (Kong et al., 2000). However, the deviance has to pass a certain threshold to elicit an N2; Daffner et al. (2000) presented participants with geometrical shapes in an oddball task. Depending on the predominant stimulus category (where targets were either simple or complex geometric shapes), an N2 was only observed for non-targets drawn from a different stimulus category. In contrast, when a non-target was from the same category as the standard stimulus, even a new shape that has not been presented before did not elicit an N2. This suggests that a missing repetition of a stimulus alone is not driving the effect of an N2. The N2 is also not elicited by a mere mismatch of stimuli. Gao et al. (2010) let participants study a colored simple shape or a complex Landolt-C, while the electrophysiological signal was recorded. For either stimulus type, however, participants were instructed to only attend the color, but not the shape of the stimuli. The test display was either completely identical, a relevant color change happened to one of the stimuli, an irrelevant shape- or gap-change happened, or both the relevant and the irrelevant feature of one stimulus changed. Compared to no-change trials, a significant N2 was evoked during relevant- and both-feature changes (for similar results, see Yin et al., 2012). However, only irrelevant changes to highly-discriminable features (that is, the simple shapes, but not the gap-orientations) elicited a slightly delayed N2 with smaller but significant amplitude. Thus, physical differences are not sufficient to elicit the N2; the change has to grab some form of the observer's attention. In sum, these results indicate that the N2 represents the detection of a "*mismatch of a stimulus with a mental template*" (Folstein & van Petten, 2008, p. 157).

A frontal N2 is also elicited if multiple stimuli have to be retained and evaluated. Yin et al. (2012) let participants study three colored shapes but instructed them to only attend the shape. A significant N2 was observed if all stimulus features were changed. If only the relevant or the irrelevant feature was changed, the amplitude of the observed N2 was less pronounced but significantly larger than during no-change trials. Similarly to findings from S1-S2-matching tasks, Gao et al. (2010) found that also for multi-stimulus memory arrays, task-irrelevant changes to complex object features are less likely to evoke an N2 mismatch signal compared to simple object features. This result could be replicated for participants with low and high WM capacity (Zhou et al., 2011).Thus, findings from studies that investigate the role of the N2 in multi-stimulus tasks indicate that the effects of the N2 are not restricted to single-stimulus paradigms. Moreover, an N2 signal can be elicited by task-relevant and highly discriminable task-irrelevant information.

In sum, there is accumulating evidence that—in the visual domain—the N2 is found to be related to the processing a mismatch between a template currently held in WM and an incoming perceptual input (Folstein & van Petten, 2008). The N2 thus provides an electrophysiological correlate to indicate if specific information is involved in target evaluation at test. If intrinsic and extrinsic feature processing in WM differ in this respect (see Ecker et al., 2013), differences in the N2 signal should be observed. This question is addressed in Experiment 4 of the present dissertation project.

1.3 THE UNIT OF WM STORAGE

The investigation of processes involved in the short-term retention of information is related to the question of "what" is actually represented in WM. As pointed out by Brady et al. (2011), "*any estimate of memory capacity must be expressed with some unit, and what counts as the appropriate unit depends upon how information is represented*" (p.5). Thus, the question of what limits visual WM is strongly intertwined with the search for the nature of the WM representation. Different phenomena can be observed that describe possible mechanisms limiting visual WM. Within the next sections, we will discuss how these findings contribute to a better understanding of what remains represented in WM when the to-be-remembered information is no longer visible. In the visual domain, the most prominent debate focusses on the topic whether the integrated objects is the unit stored in WM, or whether the number of object features influence WM functioning. The visual pattern of how the to-be-remembered information is distributed appears to be an additional factor which has more seldom been considered relevant for visual WM.

1.3.1 WM STORES INTEGRATED OBJECTS

A large body of research based on the change detection task has led to the assumption that the visual WM stores integrated objects. That is, if an object is stored in WM, all features that comprise the object are automatically bound in the representation of the object. Since the object as a whole is the operating unit, adding more features does not come with a cost (e.g., Fukuda, Awh, & Vogel, 2010; Luck & Vogel, 1997; Vogel et al., 2001). Supporters of object-based WM representations argue that WM capacity is defined by the pure number of objects that can be retained, while the number of features contained in each object is not decisive.

An influential study to systematically investigate visual WM capacity was performed by Luck and Vogel (1997). In their work, participants solved a change detection task where the number of features incorporated in each object was systematically varied. Participants performed virtually identical when they had to monitor all features of multi-featured objects (i.e., size, presence of a gap, orientation, and color), or only a single feature (i.e., only the color). WM performance was, however, strongly influenced by the number of objects: if more than four objects had to be retained, WM performance significantly decreased. Most interesting, the same result was found for associations of features from different (e.g., color-shape) and same dimensions (e.g., color-color). As there were no observable costs for remembering more features, the authors concluded that—at least in the visual domain—the whole object is selected as the unit of representation and features are automatically integrated within the representation. In support of this assumption, Zhang and Luck (2008) showed that if the number of objects presented exceeds the capacity limit of the participant, detailed representations of a few objects are remembered whilst no information about the other objects is retained. This implicates, that the visual WM operates with integrated objects in an “all-or-none” manner: either the complete object or nothing is remembered. In line with this interpretation, findings from Gajewski and Brockmole (2006) showed that participants rather fail to explicitly retrieve all features of an object instead of only isolated features. Strong object-based approaches follow the assumption that the visual WM capacity is limited to a maximum of approximately three to four objects. The object is the unit of representation and the integration of more features into the object representation is considered a rather automatic or cost-free process. Information about the object is either completely remembered or completely forgotten.

Electrophysiological findings support object-based approaches to WM: Vogel and Machizawa (2004) found that the CDA tracks the number of objects currently held in WM. Its maximum amplitude is highly correlated to the observers maximum WM capacity: the more objects a participant retains in WM, the larger the observed CDA amplitude is (see Luria et al., 2016, for review). Luria and Vogel (2011) observed that—although there appear to be initial demands to integrate features from the same dimension—these costs disappear as soon as the corresponding object is fully consolidated. This suggests that even for complex or bi-colored objects, features can be integrated into an object representation.

To sum up, a strongly object-based approach on visual WM suggests that the integrated object and not the objects’ features are the major limiting factor to WM. The integrated object is the unit represented in WM. However, although this position is supported by a series of studies (e.g., Cowan, 2001; Raffone & Wolters, 2001; Vogel et al., 2001), other findings have challenged this approach.

1.3.2 WM IS INFLUENCED BY FEATURE LOAD

Incompatible with a strong object-based WM approach, research suggests that visual WM is influenced by a number of factors that increase (or decrease) the likelihood that an object feature is transferred into a WM representation. These factors include the number of features integrated into the object and how these features are distributed across the object.

Behavioral as well as electrophysiological data point toward the conclusion, that remembering more features within an object is associated with costs in WM performance. Oberauer and Eichenberger (2013) found that participants were better able to remember single-feature objects compared to objects consisting of multiple features. Similarly, Olson and Jiang (2002, Experiment 4) found that when the number of to-be-remembered objects was held constant, remembering single features resulted in a better performance than remembering objects with multiple features. Such observations contradict that WM operates in an all-or-non manner.

The extension of the change detection paradigm by the continuous report allows the analysis of possible costs in precision and representation that can arise if more features have to be memorized per object. In the continuous report, participants do not respond in a two-alternative-forced-choice manner (same/different) but reconstruct a given feature on a continuous scale. For example, participants are asked to indicate the orientation of a formerly presented arrow on a 360° scale (see, e.g., Fougnie & Alvarez, 2011). Using the continuous report paradigm, Fougnie et al. (2010) investigated the costs of storing additional object features for WM performance. Participants viewed three colored arrows and were asked to either attend only one feature (color or orientation of the arrow) or both. The authors evaluated the costs caused by changing the task from storing three to six associated features. The continuous report method allowed the evaluation of the probability with which a feature was represented and the corresponding precision of the features representation. Storing more features was accompanied by a lower precision of the corresponding WM representations. The probability that the corresponding object was represented at all was largely unaffected. If the color was not a surface feature of the shape but presented as a separate object (i.e., spreading 3 color and 3 shape features across 6 objects), again, the precision of the WM representation was significantly affected if both features had to be monitored. However, with separated feature presentation, the probability that a feature was represented at all was significantly affected. Most important, a similar result was obtained if the color and shape features were presented at the same location but as disjunct features (i.e. color and shape did not share a common outline).

Thus, feature load as well as the manner in which features are distributed influence WM on a behavioral level.

Findings from electrophysiological research point toward a similar conclusion. Wilson, Adamo, Barense, and Ferber (2012) found that the CDA differentiates between WM representations of single- and multi-featured objects. Luria et al. (2010) contrasted the storage demands of varying numbers of simple and complex objects (e.g., color patches, random polygons). The authors found that while the CDA increased in parallel to the number of simple objects, it reached an earlier plateau for complex objects, suggesting that the maintenance of information is not only limited by the number but also by the visual complexity of the information (similar results were obtained by Gao et al., 2013). The results yielded indications that the CDA reflects the number of objects but is also influenced by feature load of the object.

Nevertheless, there is a frequently observed object-based advantage as soon as more features are task-relevant. Features are better remembered if they originate from the same item. For example, Olson and Jiang (2002) reported that participants performed better in a change detection task if object features conjoint within the same contour compared to conditions where the same features were presented as separate objects. Xu (2002b) manipulated whether to-be-remembered information were inherent parts of an object, stemmed from different parts of an object, or were disjunct from each other. She found that monitoring multiple compared to single features was largely free of cost as long as the respective features were part of the same perceptual unit. However, when features were presented at different parts of an object (i.e., Saturn-like objects with color and orientation information), performance decreased if participants monitored both compared to only a single feature. These costs were even more pronounced if features where presented as isolated objects (see, e.g., Experiment 2 and Experiment 3 from Xu, 2002b). Comparable results were obtained if the visual format was defined by figure-ground separation or negative minima of curvature (see, e.g., Experiment 5 from Xu, 2002b, or see results from Delvenne & Bruyer, 2006, or Xu, 2002a, 2006). Thus, the visual pattern with which features are distributed across objects influence the likelihood with which the corresponding information is transferred into WM.

In sum, neither encoding nor forgetting of the complete set of an object's features seems to be mandatory and holistic. The all-or-none processing of object features appears to represent the two endpoints of a continuum. Moreover, the likelihood of an object feature being represented in WM is influenced by the visual pattern of how object features are presented.

1.3.3 ARE FEATURES INDEPENDENT?

Findings yielding the influence of feature load on WM raise the question, whether encoded object-features are stored as integrated objects as long as they originate from a common object source. If this is the case, one would have to expect that object features integrated into a common representation would also be lost as a common representation. The loss of the representation of an object feature should therefore not occur independently of the loss of the other object features. However, experimental results contradict this assumption. Fougnie and Alvarez (2011) let participants study arrays with colored arrows. After a short retention, participants were required to first indicate the orientation of one of the arrows presented during the study array. This task was immediately followed by a request to indicate the corresponding color of the arrow (or vice versa). Object-based models would suggest that errors to object features are highly correlated. However, Fougnie and Alvarez found object features to fail independently, that is, participants were able to recall an object's color while not remembering the object's shape (for similar results, see, Bays, Wu, & Husain, 2011; Vul & Rich, 2010; but see Gajewski & Brockmole, 2006). Similarly, Fougnie, Cormiea, and Alvarez (2013) let participants study five colors and five arrows either presented as separate objects (10 distinct objects, arrows plus color dots) or as multi-featured objects (5 colored arrows). Although storing features presented within a common object improved WM performance, the authors found that this performance was not due to feature integration as participants could independently fail to retrieve one feature but still recall the other. Under some conditions, feature information can thus be lost independently from other object information.

Wheeler and Treisman (2002) argued that the visual WM could be organized in independent feature stores that function in parallel: objects with multiple features could be stored as well as single features, as long as none of the individual stores is exhausted (see also Olson & Jiang, 2002). In line with the assumption of individual feature representation, Delvenne and Bruyer (2004, Experiment 1) found that remembering multiple features from the same feature dimension (e.g., color-color) is associated with increased WM costs in terms of reduced recognition performance compared to feature from different dimensions (e.g., color-shape). Olson and Jiang (2002) therefore argued for a "weak" integrated object-based approach: WM is superior for features from a common object if these features are of different dimensions.

Hence, features are not mandatorily represented as an integrated object in WM under all conditions and can be independently retained. However, although the amount of to-be-remembered features influences WM performance, there appears to be an advantage for remembering features that are inherent parts of the encoded object itself.

1.3.4 ARE REPRESENTED FEATURES BOUND TO THE OBJECT?

Although different object features can be jointly encoded, the correct consolidation and maintenance of these feature assignments to an object represents another problem for the visual WM. There appears to be the need for some information about which feature was associated to which object. This process is often termed the “binding problem” (for an extensive overview, see, e.g. Zimmer, Mecklinger, & Lindenberger, 2006).

Wheeler and Treisman (2002) pointed out that binding the correct features to their corresponding objects and maintaining these fragile bonds is another factor that has to be considered for WM functioning. To test this assumption in a WM test such as the change detection task, a change from study to test is not produced by introducing a feature that was not presented during the study phase (see, e.g., Luck & Vogel, 1997). Instead, Wheeler and Treisman recombined features from study to test (for an example, see, e.g., *Figure 1*). Please note that if a change is realized from study to test by introducing a completely new feature, it is sufficient for the observer to discover this new feature as "unknown" to solve the task correctly. The observer does not need to have any knowledge about the association of the features within the objects. However, if features are recombined, it is no longer sufficient for change detection to recognize a feature as “unknown”. Instead, the associations of the features to the correct objects must be remembered since all features presented are known features from the study array. Results from Wheeler and Treisman (2002) indicated that these feature bindings are especially fragile and susceptible to interference (for similar suggestions, see results from Ecker et al., 2013; Parra, Abrahams, Logie, & Della Sala, 2009; Stefurak & Boynton, 1986). This suggests that some form of cognitive resource has to be spent to maintain correct feature bindings. Furthermore, Treisman and Zhang (2006) let participants study multi-featured objects (colored shapes). At test, participants were only required to indicate whether a new color or a new shape was presented, while paying no attention to any exact feature combination. Nevertheless, binding changes (recombinations) influenced WM performance. Treisman and Zhang, therefore, suggested that binding could appear as an automatic component of WM processing.

However, data on binding performance is far from being conclusive. For example, to test the cognitive demands of the binding process, Allen et al. (2006) let their participants perform a secondary task parallel to a change detection task. The change detection task was, thus, either performed alone or with the additional requirement to count backward or to memorize and recall digits. Compared to memory for single features, binding performance was not more affected from the dual task performance than WM performance for the least salient feature. Comparable results were obtained by Morey and Bieler (2013) as well as Johnson, Hollingworth, and Luck (2008). Although binding thus places a demand on the visual WM, it is unclear which available resources of the WM are consumed.

In sum, the findings presented above suggest that visual WM is not limited by a specific number of automatically integrated objects. Rather, WM performance is also influenced by the number of features integrated in each object and the visual complexity of those (see also Cowan et al., 2013). Although the influential effect of the number of features might not be observed under all circumstances, the visual properties of the to-be-encoded information appear to influence the mental processing requirements necessary to represent the information. Most important, this does not contradict the assumption that the visual WM is object-based, but the findings indicate that the cognitive demands to integrate information in the corresponding representations can vary. The role of cognitive demands for retaining the correct bindings between object features remains unclear (cf. Wheeler & Treisman, 2002). One factor that might have an increased impact on WM performance is the visual distribution of the to-be-remembered information, that is, the pattern of how the visual features are presented in the environment. The question thus arises whether the integration of object-inherent features differs from the integration of object features that are not part of the objects inner contour?

1.4 DIFFERENT TYPES OF FEATURE BINDING

Since visual information can vary broadly, it is possible that different cognitive processes are required depending on what information units have to be transferred into WM. For example, if it is necessary to bind objects and their surface features or bind the relations between separate visual object parts (Fougnie et al., 2010). WM might not solely be influenced by the number of objects or features perceived but also by the manner of how features are associated to each other. Storing different types of visual information could, therefore, result in varying recognition performances or different decrements associated with functional brain-changes, such as structural damage or age-related deterioration, as proposed by Allen (2015).

Indeed, it has been proven informative to examine the difference between processing features in WM that are visually inherent to an object versus features that are parts of an object but not inherent to the object’s boundaries. Based on earlier studies focusing on perception (e.g., Asch, Ceraso, & Heimer, 1960; Garner, 1974; Wilton, 1989), a distinction between *intrinsic* and *extrinsic* object features has contributed to a better understanding of both LTM and WM processes (for overviews, see, e.g., Allen, 2015, Zimmer et al., 2006, Zimmer & Ecker, 2010). Beyond mere perceptual principles that are rather peripheral to WM processes (e.g., Kahneman, Treisman, & Gibbs, 1992), Troyer and Craik (2000) referred to an intrinsic object feature as an "*incidental aspect of the stimulus itself, such as colour, font, or the voice of presentation*" (p. 161). In contrast, extrinsic object features are "*not part of the stimulus itself, but presumably part of the overall encoded event*" (p. 161). In the visual domain, intrinsic binding refers to the association of information that is inherent to the objects perceptual unit, for example an object's shape and its color; extrinsic binding defines the association of contextual information that is part of the overall event to the objects perceptual unit, for example the object's background or location (Allen, 2015). Similar mechanisms are also referred to as conjunctive and relational binding (Mayes, Montaldi, & Migo, 2007), or intra-item and relational binding (Zimmer et al., 2006).

With particular relevance for the present dissertation project, it is assumed that binding intrinsic and extrinsic information represents different mechanisms that rely on different neural structures. Based on their model of LTM functioning (Zimmer & Ecker, 2010), Ecker and colleagues (2013) proposed that the distinction between intrinsic and extrinsic binding processes might provide a general mechanism involving the processing of visual information in WM and LTM. In the following chapter, we will first present the type-token model of LTM (Zimmer & Ecker, 2010) as a potential framework for the role of intrinsic and extrinsic binding. According to the model, the distinction between both binding types could provide a general mechanism between the automatic and deliberate transfer of features into representations for LTM and potentially for WM alike. We will then examine previous WM studies against the background of the assumptions raised by the model.

1.4.1 THE TYPE-TOKEN MODEL

The present dissertation project was set out to investigate how intrinsic and extrinsic features influence WM. In the following, we will elaborate on this in more detail and argue that binding mechanisms found to influence LTM performance might also be applicable to WM functioning. Besides influences on WM task performance per se, the assumed distinction between intrinsic and extrinsic binding processes has implications for changes related to cognitive functioning.

In their type-token model, Zimmer and Ecker (2010) proposed that intrinsic and extrinsic binding processes result in different types of representations in LTM that can support different memory functions. More precisely, the authors distinguish between *object tokens*, that integrate intrinsic object information, and *episodic tokens*, that integrate contextual information of the experienced episode, that is the object and its spatio-temporal context or the relational information between different objects and/or parts (Ecker et al., 2007a, 2007b; Ecker, Groh-Bordin, & Zimmer, 2004; Zimmer & Ecker, 2010).

Zimmer and Ecker (2010) discuss object tokens as the results of consolidated percepts that arise from a rather automatic perceptual process. Object tokens, thus, bind features that are delivered via relatively automatic or data-driven processes as soon as information is encoded. However, no contextual information such as time or space is included. Consolidated object token can again be compared relatively automatic or at little or no costs against new incoming information. The formation of an object token seems to be mediated mainly through activity in the perirhinal cortex as part of the ventral processing stream.

According to the authors, episodic tokens form higher-order representations that bind individual object tokens and context. Subjects can thus retrieve additional information that enriches the object to its context. In contrast to the formation of object tokens, the processing of episodic tokens is assumed to be more controlled, that is, information can be consciously accessed or inhibited. Binding of extrinsic information is considered a supplementary processing step by recruiting additional neuronal structures. It is assumed that this process is mediated by the dorsal processing stream with the hippocampus as a central structure to bind complex relational information (Zimmer & Ecker, 2010; for an overview on the role of the hippocampus for extrinsic binding, see Yonelinas, 2013). According to the type-token model (Zimmer & Ecker, 2010), storing the information of the inherent color of an object’s shape would require intrinsic binding mechanisms. Binding two disjunct perceptual information units would require extrinsic binding. In sum, intrinsic feature binding could be a byproduct of the encoding process provided by the perceptual stream, whereas extrinsic binding could be a supplementary process that is only executed if the task context demands it (Cabeza, 2006).

1.4.2 SUPPORT FROM LTM RESEARCH FOR INTRINSIC AND EXTRINSIC FEATURE INTEGRATION

In LTM, the assumptions of the type-token model are supported by behavioral, electrophysiological, and functional magnetic resonance imaging (fMRI) results. Corresponding findings were mostly achieved in the context of research on memory processes of familiarity and recollection (see, e.g., Yonelinas, 2002, for a review on familiarity and recollection). ERPs assumed to represent the awareness of familiarity are found to be affected by manipulations of intrinsic object features. In contrast, ERPs that are assumed to reflect more conscious recollection of previously encountered situations are by-and-large found to be influenced by extrinsic feature manipulations (Ecker et al., 2004; Ecker et al., 2007a; Ecker et al., 2007; Ecker et al., 2007b; Ecker, Arend, Bergström, & Zimmer, 2009; Speer & Curran, 2007). For example, in a study by Ecker et al. (2007b), participants memorized colored line drawings of everyday objects while the electrophysiological signal was recorded. Color was either an intrinsic surface feature of the object or presented as an extrinsic disjunct frame surrounding the object. ERPs of frontal old-new effects associated with item familiarity were only affected by task-irrelevant changes to intrinsic surface color but not extrinsic frame color information. Only changes to intentionally processed extrinsic information influenced ERPs related to recollection. Overall, for LTM, findings support the interpretation that intrinsic object information is an obligatory part of the representation that is compared to the incoming information. It is found to be processed independent from the observers intention (e.g., Ecker et al., 2007b). Retrieval of extrinsic context information, however, appears to be associated with more conscious retrieval.

Neuroimaging results support the procedural dissociation of perirhinal and hippocampal activity to mediate intrinsic and extrinsic binding processes, respectively. In a study by Staresina and Davachi (2009), participants studied series of colored everyday objects with color being either an intrinsic part of the object or presented spatially disjunct in a surrounding frame. Extrinsic but not intrinsic color features elicited greater hippocampal activity for later-remembered compared to later-forgotten shape-color associations. Comparable results were obtained by Cansino, Maquet, Dolan, and Rugg (2002), or Davachi, Mitchell, and Wagner (2003).

In a similar vein, patient data on LTM functioning supports the distinction between both binding types. Patient YR, who had selective hippocampal lesions, showed spared memory performance for recognition tasks involving intrinsic feature bindings. However, YR's memory performance dropped below the level of control participants if contextual extrinsic memory was probed (Holdstock et al., 2002; Mayes, Holdstock, Isaac, Hunkin, & Roberts, 2002). Moreover, in a study from Vargha-Khadem et al. (1997), three patients, who suffered from early hypoxic hippocampal damage, revealed intact performance for recognizing intrinsic feature bindings. However, they were strongly impaired on trials that demanded extrinsic object-location binding. In accordance to the distinction between perirhinal and hippocampal activity being related to ERP signatures of familiarity and recollection respectively, one of the patients showed intact ERP correlates of familiarity but no correlates to recollection, as yielded in a later study from Düzel, Vargha-Khadem, Heinze, and Mishkin (2001). These findings corroborate the assumption that different memory-related processes are engaged if intrinsic or extrinsic binding is relevant. The hippocampus is involved when associations between items or items and their context have to be stored. Activity in the perirhinal cortex area is found to be associated with storage of intrinsic bindings (for a more in-depth discussion on neuronal structure and intrinsic/extrinsic LTM processes, see, e.g., Eichenbaum, Yonelinas, & Ranganath, 2007, Mayes et al., 2007; Moses & Ryan, 2006).

1.4.3 SUPPORT FROM WM RESEARCH FOR INTRINSIC AND EXTRINSIC BINDING PROCESSES

Understanding the role of such intrinsic and extrinsic binding mechanisms during WM tasks could extend our understanding of WM functioning. However, the distinction between intrinsic and extrinsic binding has more seldom been the target of WM research. As alluded to earlier, a large body of research suggests that the transfer of features into an object representation does come with little or no costs (e.g., Cowan, 2001; Luck & Vogel, 1997; Raffone & Wolters, 2001; Vogel et al., 2001), and that binding the correct features to their corresponding objects is not more demanding than mere storage of multiple features (e.g., Allen et al., 2006; Johnson et al., 2008; Morey & Bieler, 2013). In contrast, other researchers report that the visual WM does not operate with objects as a whole: storing multiple-feature objects can come with costs, suggesting that multiple mechanisms exist that influence whether the integration of information in WM is a demanding process or not (e.g., Bays et al., 2011; Fougnie & Alvarez, 2011; Gao et al., 2013; Luria et al., 2010; Oberauer & Eichenberger, 2013). Critically, these studies made use of stimuli that fit the definition of perceptual "intrinsic" units[1].

We argue that the mechanisms of intrinsic and extrinsic feature integration into object representations might be applicable to both LTM and WM. As presented for LTM (Zimmer & Ecker, 2010), it is assumed that—also for WM—intrinsic binding represents a mechanism that obligatorily or cost-free integrates features that are perceived as inherent to the object outline into an object representation.

1.4.3.1 Extrinsic Location Binding in WM

In WM, extrinsic binding represents the process of binding disjunct object features to contextual information. This could be temporal or spatial information, as well as relations to other objects or object parts. Previous studies showed that temporal aspects, for example the sequence in which information was stored influences binding performance

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[1] It is important to note that these findings are nonetheless in line with the assumption that storing multiple features in WM is not more demanding than storing single-feature objects if the corresponding features are intrinsic parts of the object.

(e.g., Allen et al., 2006), as well as local aspects, for example swapping locations of studied objects (e.g., Kondo & Saiki, 2012), significantly influence WM functioning. In addition, extrinsic object-location bindings were more affected by dual-task requirements than their single-feature counterparts (e.g., Elsley & Parmentier, 2009; Postma & de Haan, 1996). Moreover, such effects tend to be especially pronounced in older age groups (e.g., Mitchell, Johnson, Raye, Mather, & D'Esposito, 2000).

Most important, however, far less is known about the relational aspect of extrinsic information. Therefore, the present thesis focusses on the binding of extrinsic information defined as a disjunct relational part of the object (Ecker et al., 2013; Fougnie et al., 2010).

1.4.3.2 Extrinsic Relational Binding in WM

Assumptions of the type-token model (Zimmer & Ecker, 2010) fit the results of WM studies that compared conditions arguably correspond to the difference between intrinsic and extrinsic binding processes. Xu (2002b, 2006) found that monitoring features from different object parts comes with higher costs than if features stem from the same object part. Similarly, Fougnie et al. (2010) investigated the costs of storing multiple compared to single features: In their study, additional features were either presented as intrinsic surface features, separated objects, or as extrinsic information disjunct from the object. When additional features were presented as intrinsic surface features, monitoring more features decreased the precision of the representations. If features were presented as extrinsic information disjunct from the object or as separated objects, retrieving multiple features at test decreased the corresponding precision with which a feature was retrieved. Moreover, if additional extrinsic features had to be monitored, the probability that a feature was represented in WM at all decreased (see also Chapter 1.3.2). These findings support the interpretation that extrinsic feature processing compared to intrinsic increases the demands on WM functioning.

When memory performance was investigated with recombination tests to increase the need for explicit binding (Wheeler & Treisman, 2002), results suggest that retaining extrinsic bindings is more demanding than intrinsic bindings. Karlsen, Allen, Baddeley, and Hitch (2010) presented nameable shapes and colors either as conjoint objects or as disjunct features in mutual context. At test, either same or recombined shape-color combinations were presented. Participants performed better if the task demanded intrinsic compared to extrinsic binding. However, it is important to note that the test probe was always presented as an intrinsic stimulus. This could have led to increased interference at test, since probes deviated to a larger extent from extrinsic study displays than from intrinsic. Delvenne and Bruyer (2004; see also Ecker et al., 2013) investigated the influence of the visual format on binding performance for abstract shapes and textures in a change detection task. In one condition, the shapes were either presented as intrinsic objects with texture being an inherent part of the shape, or features demanded for extrinsic binding with shapes being presented with textures as a direct contextual background. When participants were required to solve a change detection task, the authors found that the correct bindings of multi-featured objects could be stored almost as good as single features (only the shape or only the texture) if the features were intrinsic components of the object itself; maintaining correct binding information of features that where not part of the object's contour was found to be more demanding. Moreover, RT latencies were larger for extrinsic compared to intrinsic and feature memory. The authors suggested that this might reflect the recruitment of additional processes necessary to evaluate bound extrinsic WM representations (Delvenne & Bruyer, 2004, Experiment 2A), leading to the suggestion that extrinsic binding could be supplementary to intrinsic binding in LTM as well as WM.

In line with the results indicating that extrinsic binding mechanisms are more demanding than intrinsic binding mechanisms, some studies found extrinsic binding processes to be more prone to interference. Van Geldorp, Parra, and Kessels (2015) investigated the demands of intrinsic and extrinsic feature binding by adding a concurrent secondary task (counting backward in ones) to a change detection paradigm. Stimuli were abstract shapes with colors being either presented as an inherent part of the shape or as an extrinsic color patch connected to the shape. At test, participants reconstructed the to-be-memorized items from a given set of shape and color features. In addition to a benefit of intrinsic stimuli, the authors observed that extrinsic shape-color binding was more susceptible to interference than intrinsic shape-color binding (see also Walker & Cuthbert, 1998, for comparable results). Karlsen et al. (2010) manipulated the task demands by requiring participants to count backward in threes during some but not all trials of a change detection task. Contrary to the assumptions raised above, the authors found that backward counting equally affected intrinsic and extrinsic feature binding. Findings on susceptibility to interference thus remain inconclusive. However, the fact that Karlsen and colleagues did not find the additional task to influence intrinsic and extrinsic binding to different extents does not necessarily imply that intrinsic and extrinsic feature binding do not differ. As argued by Karlsen and colleagues themselves, it might be the case that "*although the binding of separated features does not critically rely on executive attention, it also does not emerge automatically through perceptual processes in the same manner as unitized binding*" (p. 301).

Compelling evidence for different intrinsic and extrinsic binding processes in WM is provided by Ecker and colleagues (2013). In their study (Experiment 3), participants were instructed to encode intrinsic and extrinsic colored shapes. The researchers adapted the change detection paradigm by subsequently rendering one feature irrelevant to the task. This was done via an acoustic signal during the maintenance phase. In the critical condition, color was rendered irrelevant. At the time of test, participants then had to make a speeded choice, whether the shape feature of a presented colored shape was same or different to one of the shapes presented during the study array. Please note that if irrelevant feature information is changed from study to test, it should only influence WM performance if the task-irrelevant information is part of the representation that is used to evaluate the test probe. If no task-irrelevant information is represented during the test phase, no interference effects to recognition performance or RT latency should be observed. In their study, Ecker et al. (2013) found that distracting effects were larger for intrinsic compared to extrinsic irrelevant color changes. Although complete objects were encoded during the study phase, only changes to task-irrelevant intrinsic color features influenced WM performance at test. Moreover, participants were, in fact, able to report the studied color for both intrinsic and extrinsic stimuli if asked. This suggests that intrinsic but not extrinsic information is obligatorily retrieved at test, although an intentionally engaged retrieval of extrinsic information is possible. This effect was found for new-feature changes as well as recombinations, suggesting that binding processes are more automatic for intrinsic compared to extrinsic stimuli.

Ecker and colleagues (2013) further examined this interpretation by adapting the to-be-remembered stimuli. By varying the overall background and the 3-dimensional presentation of the shape information, stimuli that were previously defined as extrinsic could then be perceived as intrinsic: Instead of a shape presented on a colored square against a uniform background, the stimulis’ former shapes could be perceived as keyhole-like information with the surrounding color patch forming the actual shape (unitized condition, Experiment 4, Ecker et al., 2013). In the control condition, the background color around the square color patch was changed, so that no keyhole-like impression was constructed (separable condition). Strikingly, the results indicated that color information that was processed as extrinsic in previous tasks was now processed as the basis of the shape. Task-irrelevant changes to color did now affect performance in the unitized condition, but, again, not in the separable (i.e. extrinsic) condition. The authors concluded that color information becomes obligatorily part of the representation retrieved at test as soon as the information can be perceived as an intrinsic surface feature of a shape. Similarly, in a study from Xu and Chun (2007), participants encoded objects that were either grouped within black rectangles or distributed across them. Although the rectangles were irrelevant to the actual task, "*the groupings between these shapes were still encoded by the inferior* [intraparietal sulcus] *IPS, suggesting that this brain area may represent the overall hierarchical structure present in a visual display, independent of the level of attentional selection*" (Xu & Chun, 2007, p. 18769).

In sum, although both intrinsic and extrinsic bindings can be stored in WM, there is accumulating evidence that intrinsic object features are involuntary part of the representation available at test. The retrieval of extrinsic information involves more deliberate processing. Moreover, this appears to be observed for feature as well as bound information.

1.4.4 NEUROPSYCHOLOGICAL INDICATIONS THAT INTRINSIC AND EXTRINSIC FEATURE BINDING DIFFER IN WM

The type-token model can be used to derive assumptions about how the WM performance for intrinsic and extrinsic stimuli should change when relevant brain structures are damaged. As argued by Ecker and colleagues (2013), if the hippocampus is crucial for binding extrinsic information, damage or deterioration to this structure should not only cause LTM binding impairments but should also lead to increased losses in WM functioning for extrinsic compared to intrinsic feature bindings. In line with this assumption—although the hippocampus is typically regarded to be of critical importance for LTM processes (e.g., Brown & Aggleton, 2001; Eichenbaum et al., 2007)—there is an increasing number of positions suggesting that the hippocampus is necessary for the association of information units in general, detached from the temporal domain. It is argued that intact hippocampal functioning is required in particular for the association of relational information (e.g., Konkel & Cohen, 2009; Yonelinas, 2013).

Indeed, multiple fMRI experiments have shown that the hippocampus is involved in the processing of extrinsic information, for LTM as well as WM tasks. For example, fMRI results from Hannula and Ranganath (2008) indicated that neural activity in the hippocampal brain region predicts successful extrinsic but not intrinsic feature integration in WM. In their experiment, participants studied everyday objects arranged in a room-like field. After short retention, participants saw a test display with either similar or re-arranged object relations. Hippocampal activity was related to a correct match between retained and encoded object relations. Results support the assumption that the hippocampus might be of critical importance for encoding and retrieving extrinsic spatial object-location and relational object-object associations not only during long but also short delays. However, no such involvement in extrinsic binding processes was observed for the perirhinal cortex (for similar results, see Hartley et al., 2007; Piekema et al., 2009; Piekema, Kessels, Mars, Petersson, & Fernández, 2006; Piekema, Kessels, Rijpkema, & Fernández, 2009; Piekema, Rijpkema, Fernández, & Kessels, 2010). In contrast to extrinsic binding, intrinsic binding performance is found to be related mainly to increased activity in parietal, occipital, and temporal brain regions (Parra, Della Sala, Logie, & Morcom, 2014; Piekema et al., 2006; Piekema et al., 2010; Shafritz, Gore, & Marois, 2002). Thus, studies investigating brain activity using fMRI techniques appear to support the distinction between intrinsic and extrinsic information processing in WM.

Similarly, streams of neuropsychological research support the distinction of intrinsic and extrinsic binding in WM. Hannula, Tranel, and Cohen (2006) compared patients with selective hippocampal damage due to anoxic/hypoxic episodes in a WM task. Participants had to store the associations between faces and the context the faces appeared in (landscape pictures). Compared to healthy adults, patients with hippocampal damage performed significantly worse for remembering extrinsic object-context association during long and short delays (comparable results were obtained by Olson, Moore, Stark, & Chatterjee, 2006; Olson, Page, Moore, Chatterjee, & Verfaellie, 2006; Parra et al., 2015). However, Baddeley, Allen, and Vargha-Khadem (2010) investigated intrinsic and extrinsic binding performance of patient Jon, who suffered from memory impairments due to premature birth and subsequent breathing problems that led to hippocampal damage. In contrast to the findings reported above, Jon did not perform worse than the control subjects during visual WM binding tasks.

Taken together, these results from neurophysiological WM studies are partially in line with the assumptions raised in the type-token model (Zimmer & Ecker, 2010): Integrating intrinsic and extrinsic features appear to differ at a structural level, with the hippocampus being critically involved in extrinsic but not intrinsic feature processing (but see Piekema et al., 2007).

1.5 INTERIM SUMMARY

The reported studies suggest that the visual WM does not operate with integrated objects under all conditions. The distribution of information across objects is found to significantly influence WM functioning. Within the scope of the present thesis, the reviewed studies suggest the following: although there appears to be an advantage for storing features that are intrinsic to the contour of an object, the visual distribution of the information processed during WM tasks influences what mechanisms are recruited in WM to retain the corresponding information. In sum, compared to extrinsic binding, intrinsic binding has been found (a) to arise more involuntarily (Ecker et al., 2013), (b) to be less susceptible to interference (Allen, Hitch, Mate, & Baddeley, 2012; Delvenne & Bruyer, 2004; van Geldorp et al., 2015), (c) to be less affected by articulatory suppression (Walker & Cuthbert, 1998), and (d) to be associated with better associative memory performance (Delvenne & Bruyer, 2004, 2006; Xu, 2002b, 2002a). In addition, although extrinsic binding has been associated with activity in the medial temporal lobes and the hippocampus (Hannula & Ranganath, 2008; Parra et al., 2015; Piekema et al., 2006; Piekema et al., 2009; Piekema et al., 2010), intrinsic binding has been linked to activity in parietal, occipital, and temporal brain regions (Parra et al., 2014; Piekema et al., 2006; Piekema et al., 2010; Shafritz et al., 2002).

Hence, there is a fair amount of research indicating that a clear understanding of what drives the difference between intrinsic and extrinsic information processing can significantly contribute to our knowledge about visual WM functioning. Findings from LTM research within the scope of the type-token model (Zimmer & Ecker, 2010) suggest that different binding mechanism could explain the distinction between intrinsic and extrinsic information processing in WM. Clear hypotheses can be derived from the type-token LTM model (Zimmer & Ecker, 2010) about how intrinsic and extrinsic feature binding mechanisms should “behave” in WM. Moreover, processing differences could be especially pronounced if the assumed underlying brain structures are limited in functioning. One way to gain information about these assumptions is to compare samples of different age groups. Healthy aging is associated with a variety of neurological changes that are found to influence cognitive performance. Within the next chapters, we will explain how age-related deteriorative processes could contribute to our understanding of intrinsic and extrinsic binding processes.

1.6 INTRINSIC AND EXTRINSIC BINDING AS GENERAL MECHANISMS?

Age-related changes to the human brain can contribute to our understanding whether intrinsic and extrinsic feature binding represent two essentially different mechanisms, mediated by different neural structures (see Allen, 2015, for a similar discussion). A possible vehicle for investigating the influence of neuronal function on cognitive processes is the comparison of different age groups. Certain regions of the brain are affected by characteristic age-related degradation processes that are considered to affect the performance of cognitive functions (e.g., Fjell & Walhovd, 2010). Hence, in addition to the neuroanatomic distinction assumed for extrinsic and intrinsic binding mechanisms (see Chapter 1.4), corresponding assumptions can be derived from the type-token model

(Zimmer & Ecker, 2010) as to how age-related degenerative processes should affect intrinsic and extrinsic WM performance.

It is a well-established finding that memory decreases with advancing age, both with long (e.g., Craik & Rose, 2012) as well as short retention intervals (Park & Payer, 2006; Sander et al., 2012). Studies of episodic LTM have shown that elderly people show a characteristic deficit in storing associative information, in particular when it comes to specific combinations of items or combinations of items and their contexts. By contrast, memory for individual items is relatively preserved (Naveh-Benjamin, 2000; Old & Naveh-Benjamin, 2008, for a meta-analysis). Interestingly, although such an age-related association deficit is consistently reported for LTM, a corresponding deficit in short-term memory or WM has been reported only in some studies (Borg, Leroy, Favre, Laurent, & Thomas-Anterion, 2011; Brown & Brockmole, 2010; Chen & Naveh-Benjamin, 2012; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006; Fandakova, Sander, Werkle-Bergner, & Shing, 2014; Mitchell, Johnson, Raye, Mather et al., 2000) but not others (Brockmole & Logie, 2013; Brockmole, Parra, Della Sala, & Logie, 2008; Brown & Brockmole, 2010; Brown, Niven, Logie, Rhodes, & Allen, 2017; Parra et al., 2009; Rhodes, Parra, & Logie, 2016). The question thus arises: What is the factor that differentiates studies that have demonstrated an age-related association deficit in WM from studies that have not?

1.6.1 AGE-RELATED CHANGES TO ASSOCIATIVE LTM PERFORMANCE

In LTM, the association deficit is typically assessed by pair recognition tasks. Participants study lists of items consisting of, for example, pairs of objects or objects in item-unique spatiotemporal contexts. Subsequently, participants are required to recognize old pairs among recombined and/or new pairs (e.g., Naveh-Benjamin, 2000). In a study from Moshe Naveh-Benjamin (2000), younger and older participants studied lists of words written in different fonts. Participants were instructed to either memorize only the words, the fonts, or the associations between the words and their corresponding fonts. While older adults' memory performance for the individual features was virtually identical to memory performance of younger adults, older participants showed severe impairment in retrieving the associations of words and fonts. To this day, such an age-related association deficit (Naveh-Benjamin, 2000; see also Chalfonte & Johnson, 1996) has been observed across numerous types of stimuli and tasks, as reported in a meta-analysis by Old and Naveh-Benjamin (2008).

Age-related changes to the hippocampal structures are discussed as one major root for the association deficit (Cabeza, 2006). According to the hippocampal-relational-memory view, correct hippocampal functioning is inevitable for relational memory (e.g., Brown

& Aggleton, 2001; Eichenbaum et al., 2007; Mayes et al., 2007; Moses & Ryan, 2006). For example, a meta-analysis from Aggleton and Brown (1999) revealed that lesions to hippocampal structures result in significantly larger deficits in relational (i.e. extrinsic) memory than item memory, whereas losses in the latter performance was more closely associated with perirhinal damages. The hippocampal brain area is particularly affected by age-related degradation processes and structural changes. For example, speeded morphological changes to the hippocampus are observed to begin around the 60th year of life (Yang, Goh, Chen, & Qiu, 2013). Compared to adjacent brain regions, such as the entorhinal cortex, hippocampal tissue is found to undergo a significantly fast shrinkage within a small amount of time (Raz, Ghisletta, Rodrigue, Kennedy, & Lindenberger, 2010; for comparable findings, see also Fjell & Walhovd, 2010; Raz et al., 2005; Shing et al., 2010). Hence, degradation processes to hippocampal brain structures are discussed as one major factor driving occurrence age-related associative deficits.

1.6.2 AGE-RELATED CHANGES TO ASSOCIATIVE WM PERFORMANCE

As introduced in Chapter 1.2.1, to assess associative memory performance in WM, variants of change-detection paradigms are often used. In this paradigm, the association usually refers to combinations of item features, for example the bindings of item shapes and their colors (e.g., when deciding whether the color feature of one of the items in the display has changed from study to test). In some tasks, however, the association refers to the bindings between items and their locations or contexts (e.g., when deciding whether the spatial item configuration has changed). Performance in these conditions is then compared to memory for the item features themselves (for an overview, see, e.g., Allen, 2015).

We argue that these procedural task differences—specifically which type of binding is assessed—may be critical for the presence or absence of an age-related binding deficit in WM. In fact, studies that found no evidence for age-related association deficits in WM have tended to focus on bindings between items and their surface features, that is intrinsic feature processing, whereas studies suggesting age-related association deficits have tended to focus on bindings between items and their locations or spatiotemporal contexts, that is extrinsic features.

1.6.2.1 Indirect Comparisons of Age-related Changes to Intrinsic and Extrinsic Binding

As stated above, extrinsic but not intrinsic binding relies on the integrity of hippocampal structures (e.g., Staresina & Davachi, 2009). This is based on the position that the hippocampus is involved in relational forms of binding, irrespective of the time domain, that is the length of the delay from the time the information was encoded until the information is tested (Konkel & Cohen, 2009; Yonelinas, 2013). As the hippocampal structures found to be especially prone to age-related changes (Fjell & Walhovd, 2010; Raz et al., 2005; Raz et al., 2010; Shing et al., 2010; Yang et al., 2013), it follows that extrinsic binding abilities should decline with age more strongly than intrinsic binding abilities.

Indirect evidence for differential effects of aging on extrinsic versus intrinsic binding in WM comes from the comparison of studies using intrinsic conditions with those using extrinsic conditions. Studies focusing on intrinsic binding have by-and-large failed to find age-related binding deficits in WM. For example, Brockmole and Logie (2013) investigated WM performance of more than 55,000 online participants from different age groups in a change-detection paradigm probing intrinsic shape-color binding. Although older participants showed poorer item memory performance than younger participants, they demonstrated only minimal binding impairments. Similar results have been found in lab studies (Brockmole et al., 2008; Parra et al., 2009), even with extended encoding times (Brown et al., 2017; Rhodes et al., 2016), or the addition of a secondary task (Brown & Brockmole, 2010, but see their Experiment 2). Likewise, Isella, Molteni, Mapelli, and Ferrarese (2015) reported only a small and nonsignificant age effect on shape-color binding. Overall, these findings imply that intrinsic binding is not substantially more affected by age than WM for items (i.e. features).

By contrast, age-related binding deficits have been demonstrated with WM tasks that arguably require extrinsic integration, such as object-location binding with figural objects (Cowan et al., 2006; Mitchell, Johnson, Raye, & D'Esposito, 2000; Mitchell, Johnson, Raye, Mather et al., 2000), letters (Fandakova et al., 2014), emotional pictures (Borg et al., 2011, although binding was not contrasted with item memory in this study), and abstract shapes (Peich, Husain, & Bays, 2013). An age-related deficit in object-location binding seems to exist in WM – however, it might be present only under demanding procedural conditions. For example, when Rhodes, Parra, Cowan, and Logie (2017) excluded duplicate stimuli from the paradigm used by Cowan et al. (2006)—thus reducing the executive control necessary to prevent interference—they did not find an age-related binding deficit. Similarly, Read, Rogers, and Wilson (2016) did not find an age-related binding deficit when they controlled for interference from multi-stimulus probes. Moreover, as pointed out by Rhodes et al. (2017), the reported evidence may be weaker than it first appears because in some studies (e.g., Borg et al., 2011; Fandakova et al., 2014; Mitchell, Johnson, Raye, Mather et al., 2000), only significant versus nonsignificant simple main effects were reported but not a significant interaction effect (Nieuwenhuis, Forstmann, & Wagenmakers, 2011). With regard to object-context binding, Chen and Naveh-Benjamin

(2012) reported a binding deficit in older adults if participants were required to memorize the associations between faces and scenes presented as backgrounds. The comparison between these two lines of research indicates that intrinsic and extrinsic binding processing do dissociate in older age. However, this conclusion is based on the indirect comparison of individual studies each using a particular type of stimulus.

1.6.2.2 Direct Comparisons of Age-related Changes to Intrinsic and Extrinsic Binding

To the best of our knowledge, only three studies (Bastin, 2017; Peterson & Naveh-Benjamin, 2016; van Geldorp et al., 2015) have directly compared the age-sensitivity of intrinsic and extrinsic binding in WM within the same experiment. Christine Bastin (2017) created a WM task involving real-world object line drawings with color being either a surface feature (e.g., a yellow tent) or an extrinsic context feature (i.e., the tent was presented as a black-and-white line drawing and color as a patch next to the tent). At test, participants were required to decide whether a presented object-color association was part of the study list. Compared to WM performance for single features, older but not younger adults had a disproportionately lower WM performance for extrinsic compared to intrinsic object–color associations.

Van Geldorp and colleagues (2015) tested younger and older participants in a WM task designed to investigate extrinsic (relational) and intrinsic (conjunctive) shape-color binding. The task involved reconstructing study items by assigning shapes to their study color and this was performed with or without a concurrent interfering task (counting backward). Supporting the distinction between extrinsic and intrinsic binding, overall memory performance was lower for extrinsic than for intrinsic stimuli, and the interfering task impaired memory for extrinsic items more than memory for intrinsic items. Notably, however, although older participants showed poorer memory performance than younger participants, there were no interactions involving age and type of binding even though extrinsic binding was more demanding than intrinsic binding.

Peterson and Naveh-Benjamin (2016, Experiment 1) used a change detection task requiring memory for features (shapes or colors) and contrasted this with a change detection task requiring memory for shape-color bindings. Color was either a surface feature of the shape (which was presented on a gray background square) or it was a background feature (i.e., the shape was gray and presented on a colored square). The type of binding had no effect on performance. However, Peterson and Naveh-Benjamin observed an age-related association deficit: Older people showed a larger binding deficit than younger participants. This age-related binding deficit disappeared when participants engaged in articulatory suppression during study, leaving only a main effect of age.

The hitherto available data allows three conclusions regarding age-related effects in WM: (a) intrinsic information is processed rather automatically across age groups, without any age-related impairments; (b) in some studies, extrinsic *object-location binding* was negatively affected by aging if distractor competition was high; and (c) evidence for age-related impairments in *object-context binding* is sparse and inconsistent. It remains an interesting topic of debate, what causes these inconsistent results.

1.6.3 DIRECT AND INDIRECT TESTS OF WM

One reason for the diverging results regarding extrinsic binding might lie in the explicit binding requirements of the change detection paradigm used in the majority of studies. That is, participants are typically instructed to attend to and encode feature combinations for a test that directly targets the bindings. With such a test procedure, intentional use of encoding strategies is likely (see Peterson & Naveh-Benjamin, 2016). Hence, it is possible that older people have an encoding deficit for extrinsic bindings, which they, however, may be able to compensate for by enhanced intentional effort.

One way to circumvent speculations regarding the impact of potentially obscuring variables such as strategy use and effort is to use *indirect* binding tests. Such indirect tests purport to be feature memory tests; participants are instructed to focus on and memorize a specific feature (e.g., object shapes) while ignoring other features of the presented study objects (e.g., object color or background color). To the extent that feature information is automatically transferred into the WM representation, study-test changes of the task-irrelevant feature should impair memory performance (e.g., slow down or impair recognition; Gao, Gao, Li, Sun, & Shen, 2011). For example, Gao and colleagues (2011; Experiments 1a to 2b) let participants study arrays of oriented colored gaps. Participants either monitored the gap or the color feature, thus varying the task-relevant feature that has to be retained in WM. The authors found that task-irrelevant changes to simple (color) but not complex (gap) object features prolonged RTs to the change detection task. Hence, behavioral effects when a response is given can be used to investigate the presence or absence of information in WM.

Such indirect testing paradigms have been used to demonstrate the obligatory nature of intrinsic but not extrinsic binding both in LTM (Ecker et al., 2007a, 2007b; Nicholson & Humphrey, 2004; Zimmer & Ecker, 2010) and WM (Ecker et al., 2013; Maybery et al., 2009) in young adults. Critically, no studies to date have used indirect tests to investigate WM binding in older participants.

1.7 SUMMARY

Taken together, the transfer of visual into WM is influenced by the number of to-be-remembered objects, their features, as well as by the distribution of the feature information across the object. Two binding mechanisms were identified that are assumed to be of major importance for the processing of associative information in LTM and WM. Intrinsic binding is assumed to be a rather cost-free process, that automatically or involuntarily integrates surface information to the corresponding object representation without posing large demands on WM. Extrinsic binding in WM is assumed to be a more deliberate process intentionally engaged as a supplementary (and potentially subsequent) process, that produces higher-order representations that associate individual units. Findings indicate that binding mechanisms are mediated via different neural structures. Whereas intrinsic binding is assumed to rely mainly on intact functioning of perirhinal structures, extrinsic binding is assumed to rely on intact hippocampal functioning. Despite the presence of a pronounced age-related association deficit in LTM, little is known about how such binding mechanisms influence WM performance. The present dissertation project is set out to investigate whether different binding mechanisms can explain the observed processing differences for intrinsic and extrinsic visual stimuli in WM.

Experiment 1 tackles the question, whether intrinsic and extrinsic binding processes are differently affected by age-related changes to neuronal functioning. Moreover, WM performance for intentionally and unintentionally processed stimuli is contrasted. Findings could help to identify the type of binding as a critical factor limiting WM, associated with intact functioning of perirhinal and hippocampal brain regions. Experiment 2 investigates whether differences between intrinsic and extrinsic binding performance can be related to differences in the consolidation of information into WM, that is when perceptual information is transferred into a stable WM representation. Restraining the time available to process the visual information can be used to investigate the subsequent nature of extrinsic binding. In addition, age-related constraints on the information processing should become apparent when the time available to process stimuli is systematically varied. Experiment 3 deals with the question of whether the consolidated representations of intrinsic and extrinsic information differ during the short-term retention. Neurophysiological data of slow wave potentials can help to elucidate whether both stimulus types (intrinsic/extrinsic stimuli) can be retained as integrated representations or whether the retention of extrinsic information poses increased demands on WM maintenance. Last, Experiment 4 uses electrophysiological markers of mismatch detection to investigate whether observed processing advantage for intrinsic information are based on an involuntary integration in the corresponding WM representation, while extrinsic information has to rely on an intentional direction of the focus of attention. In sum, the series of experiments allows a careful examination as to whether binding mechanisms are to a similar extent involved in WM as they are in LTM functioning.

2 EXPERIMENT 1: AGE-RELATED CHANGES IN WORKING MEMORY - AGE AFFECTS EXTRINSIC BUT NOT INTRINSIC FEATURE BINDING

The goal of the first Experiment was to contrast WM performance for extrinsic and intrinsic stimuli in young and older adults using both direct and indirect tests. Based on the existing literature outlined above, we hypothesized that memory for associations of extrinsic features should generally be poorer than memory for associations of intrinsic features. Also, no age effects were expected for intrinsic stimuli. By contrast, to the extent that extrinsic binding is affected by age, older adults should show a particularly strong impairment of memory for extrinsic associations, resulting in an interaction between type of binding and age.

The exact difference between feature memory and binding conditions depends on the degree of independence between memory for individual features and memory for bindings. In the literature, for intrinsic items, three relationships between feature memory and memory for bindings (i.e., in the intrinsic case: memory for objects) have been reported. First, some have argued for an all-or-none relationship. For example, in the study from Luck and Vogel (1997), participants remembered all features of an object or none. Thus, feature memory was completely dependent on object memory, and performance in the binding condition was at the level of feature memory performance. Second, others have hypothesized that feature memory is object-based but independent, progressing from coarse to fine (e.g., Gao et al., 2013). Based on this, one would expect that performance in the binding condition is at a similar level as performance for the most difficult-to-remember individual feature. Indeed, this result has been obtained in a number of studies (e.g., Kursawe & Zimmer, 2015; Song & Jiang, 2006; Woodman & Vogel, 2008). Finally, sometimes memory for different features has been found to be independent (e.g., Bays et al., 2011). In this case, memory for bindings is expected to be equal to the product of the recognition probabilities for the individual features, as long as memory is not positively influenced by additional binding processes or negatively affected by binding deficits.

Irrespective of the exact nature of the relationship between feature memory and binding memory, an interaction effect was expected in the present study: If older adults show a specific binding deficit, any decrement in binding memory compared to feature memory should be magnified relative to younger participants, causing an interaction between the change condition (feature vs. binding change) and age. However, if older people can invest additional effort to compensate for their extrinsic-association deficit when they are explicitly instructed to memorize the associations, then the interaction should vary with the type of test. That is, the proposed age-related extrinsic binding deficit should be evident in the indirect test but may not occur with a direct test[2].

To test these hypotheses, younger and older participants completed a change detection task. Participants studied sets of colored shapes (intrinsic stimuli) or white shapes encased in colored frames (extrinsic stimuli). Participants completed the task under two conditions: in the direct test condition, they were instructed to memorize the color-shape bindings; in the indirect test condition, they memorized only the item shapes. A single test probe was either identical to a study item (no change), it contained an unstudied shape or color (new shape, new color), or it was a new arrangement of a studied color and a studied shape (recombination). Test probes with a new color or a new shape allowed an assessment of item memory, as responses in these conditions could be made based on the evaluation of individual features rather than the specific shape-color association. By contrast, test probes recombining old features allowed an assessment of binding performance, as knowledge for the specific study associations was required for accurate performance (see Olson & Jiang, 2002; Parra et al., 2009; Wheeler & Treisman, 2002). Using a single test probe is recommended if the test involves recombinations (Cowan et al., 2013), and a single test probe is also standard for indirect tests. To keep conditions comparable, a single test probe was thus used in both the direct and indirect tests. The probe was presented in a central position to minimize influences of object-location binding on memory (Cowan et al., 2013; van Geldorp et al., 2015).

2.1 METHODS

The experiment used a fully crossed 2 (test type: direct, indirect) × 2 (stimulus type: extrinsic, intrinsic) × 4 (change type: same, new shape, new color, recombined) × 2 (age: young, old) mixed design, with age as the only between-subjects factor.

2.1.1 PARTICIPANTS

Sample size was determined by an a-priori power analysis using G*Power (Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007). To this end, we initially obtained effect-size estimates for the critical interaction between age and type of binding from previous studies reporting an association deficit, using the error terms of the analyses of variances (ANOVA). The obtained effect sizes were mostly $\eta_p^2 > .18$. Based on a

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[2] Please note that binding deficits will present as reduced memory performance for item-feature associations in the direct test and reduced costs associated with task-irrelevant study-test feature changes in the indirect item recognition test.

conservative estimate of $\eta_p^2 = .15$, the suggested minimum sample size to detect an interaction effect with power $1 - \beta = .95$ was 38 participants per group.

A total of 93 participants took part in the study; 48 were young adults (nonpsychology undergraduate students from Saarland University) and 45 were older adults. Two young and two older participants reported problems understanding the instructions, and one young participant confused the response buttons. These participants were excluded, so that the final sample size was $N = 88$, comprising $n = 45$ young adults (age range 18-33 years; mean age $M = 21.93$, $SD = 3.28$; 23 women, 22 men) and $n = 43$ older adults (age range 64-82 years; mean age $M = 71.33$, $SD = 4.61$; 30 women, 13 men).

Participants' processing speed was assessed with a digit symbol substitution test adapted from Wechsler (2008). Young participants' mean score was $M = 64.67$ ($SD = 11.65$), whereas older participants' mean was $M = 47.65$ ($SD = 9.84$). Both values are in a plausible range (see Ferdinand & Kray, 2013; Kray, Eber, & Karbach, 2008). The younger sample had more years of formal education, $Md = 13$, $M = 12.46$, $SD = 0.77$, than the older sample, $Md = 10$, $M = 10.72$, $SD = 1.65$, $U = 352.50$, $z = -4.47$, $p < .001$.

All participants reported good health, normal or corrected-to-normal vision, no history of neurological disorders (in the last 5 years), no deficits of hand mobility, and no use of medication that might influence RTs. All participants provided written informed consent after reading an ethically approved information sheet; they received a monetary compensation of €8 per hour. The study was performed under ethical approval of the Ethics Committee of the Philosophical Faculty III Empirical Human Sciences at Saarland University.

2.1.2 MATERIALS AND APPARATUS

Stimuli consisted of 24 novel complex shapes for which no common names exist. For this purpose, different simple geometric shapes were overlaid and their outline defined the border of the complex figure (see *Figure 1* for examples). Two versions of the stimuli were generated: intrinsic stimuli were fully colored shapes; extrinsic stimuli were white shapes (RGB values: 255, 255, 255) encased with a colored rectangular frame. The number of colored pixels in the frame approximated the number of pixels contained in the fully colored version of the shape, in order to achieve physically similar amounts of color information. Ten different colors were used: red (255, 0, 0); green (0, 255, 0); blue (0, 0, 255); magenta (255, 0, 255); cyan (0, 255, 255); yellow (255, 255, 0); orange (255, 102, 0); brown (153, 102, 51); pink (255, 153, 204); and black (0, 0, 0). The shape-stimuli subtended 1.98° × 1.98° of visual angle, the surrounding frame 3.80° × 3.80°. Stimuli were presented on a gray (153, 153, 153) background. The procedure was presented on a 23-inch flat-screen monitor with a resolution of 1,920 × 1,080 pixels and a refresh rate of 60 Hz. Participants were seated in front of the screen at an approximate viewing distance of 60 cm.

To ensure comparisons reflect differences in memory performance and not potential differences in sensory-perceptual abilities between older and younger participants, presentation time of study items was adjusted for each participant in order to compensate for age-related slowing of encoding. It has been shown that sensory deficits can partially account for observed differences in the associative memory measures and other cognitive deficits (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Naveh-Benjamin & Kilb, 2014). Even for younger adults, insufficient encoding time can reduce WM performance (Eng, Chen, & Jiang, 2005). To calculate the necessary adjustment for each participant, a visual search task (see Alvarez & Cavanagh, 2004; Vaughan & Hartman, 2010), adapted to estimate the individual encoding times for the main experiment, was administered prior to the actual WM task (see Appendix 1 for details). It should be noted that this adjustment only served to equate perceptual encoding across groups, without influencing memory per se; this is because longer presentation times do not enhance memory if the modulation only serves to approximate the time necessary for proper encoding (e.g., Luck & Vogel, 1997; Rhodes et al., 2016; Sander, Werkle-Bergner, & Lindenberger, 2011; Vaughan & Hartman, 2010).

2.1.3 PROCEDURE

The trial structure is illustrated in *Figure 1*. Each trial began with the presentation of a central fixation cross. After 600 to 800 ms (the exact interval was randomly determined), a cue word was presented centrally, just above the fixation cross, for 800 ms. The cue word indicated the task-type information: the cue “BEIDES” (both) was used in trials of the direct test; the cue “FORM” (shape) was used in trials of the indirect test. The fixation cross remained on the screen for another randomly chosen interval between 750 to 1050 ms after the cue word disappeared. Next, an array of three study stimuli was presented; stimuli were arranged on an invisible circle (6° visual angle in diameter) centered on the midpoint of the screen, with the three item locations forming a virtual isosceles triangle. The presentation time of the study display was on average 1,493 ms (*SD* = 293 ms) for younger, and 1,846 ms (*SD* = 291 ms) for older adults, individually adjusting for each participant’s encoding speed as estimated from the visual search task (see Appendix 1). These presentation times are in the range of other WM studies with older samples (e.g., Vaughan & Hartman, 2010).

After a retention interval of 1,000 ms, a single probe was presented in the center of the screen. On direct test trials (shape-color associations are task-*relevant*), participants indicated whether the presented shape-color combination had featured in the study display or not. On indirect test trials (new colors and color recombinations are task-*irrelevant*), participants indicated whether or not an item of the same shape had been presented during study. Participants responded by pressing a key on a Cedrus response pad (RB-834, Cedrus Corporation, San Pedro, California, USA). Response categories (match and non-match) were assigned according to participants' handedness, with match trials mapped onto the dominant hand (in case of uncertainty, handedness was assessed according to the Edinburgh inventory; Oldfield, 1971). The test display remained on screen until a response was given or for a maximum of 5,000 ms; it was followed by an inter-trial interval of 1,200 ms. Both accuracy and response speed were emphasized.

There were a total of 360 trials; half of these (180) used intrinsic stimuli and half extrinsic stimuli. For each stimulus type, half the trials (90) were direct association test trials, and half were indirect test trials. In each test condition, half the trials (45) were change trials and half required a no-change response. Thus, in the direct test, 15 trials occurred in each change condition: new color, new shape, and recombination. In the indirect test, no-change stimuli, stimuli with a new color, and stimuli with a recombined color (15 trials each) required a no-change response and 45 trials fell in the new shape category. Every 120 trials, participants could take a self-paced break. Trials were in random order. To ensure adequate understanding of the paradigm, there were 24 practice trials that were not included in analyses. Experiment 1 lasted 1.5 to 2 hours.

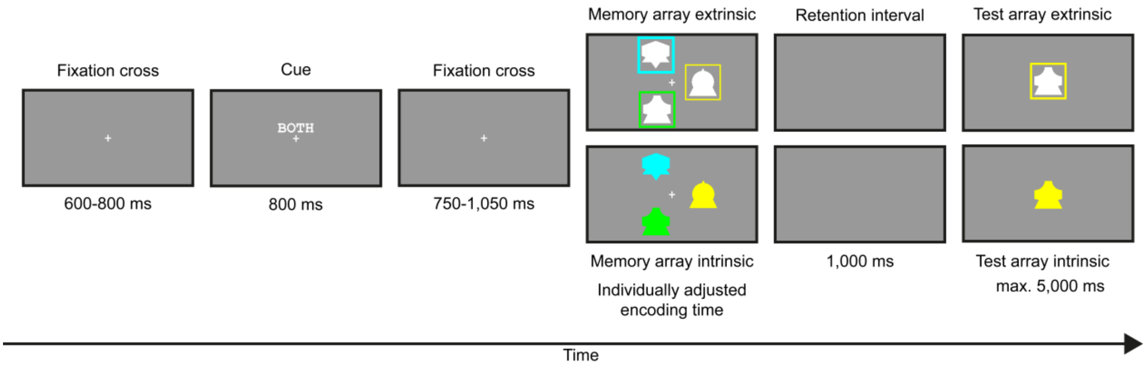

Figure 1: Schematic illustration of the trial structure in Experiment 1, not drawn to scale. A "SHAPE" cue was associated with the indirect test; a "BOTH" cue was associated with the direct test. In the example, a direct test condition with a "change" trial is depicted (i.e., the test probe is a recombination of a studied shape and a studied color and the correct response is thus "new"). The width of the colored frames in the extrinsic condition was determined by the surface area of the corresponding shape, in order to equate the number of color pixels across extrinsic and intrinsic stimulus categories.

2.2 RESULTS

Trials with RTs falling 2.2 times the interquartile range above the third quartile or below the first quartile of a participant's individual RT distribution (Hoaglin & Iglewicz, 1987; Hoaglin, Iglewicz, & Tukey, 1986), as well as trials with RTs below 200 ms were excluded prior to all analyses. This resulted in the exclusion of 2.55% of trial data and reduced the positive skew of the RT data. Nevertheless, RTs were still nonnormally distributed; we therefore based RT analysis on log10-transformed data. As results did not differ qualitatively and for ease of comprehension, we report descriptives based on the un-transformed RT data. Dependent variables were recognition accuracy and RTs. Corrected recognition scores were calculated as *Pr = hit rate – false alarm rate* (i.e., *proportion of hits + proportion of correct rejections – 1*; Snodgrass & Corwin, 1988). The *Pr* measure is associated with a two high-threshold model, which we considered plausible for the type of task administered: Participants can explicitly judge the match (or mismatch) of the test probe and their memory representation and guess if there is insufficient evidence for either a "changed" or "same" response. As direct and indirect tests required different responses, scoring and analyses were conducted separately (see Chapters 2.2.1 and 2.2.2 for details). Follow-up analyses were obtained by investigating contrasts or (Bonferroni-corrected) pairwise comparisons. In the figures, we present 95% confidence intervals (CIs) based on within-subjects variances to make a direct comparison of conditions possible (following Cousineau, 2005). In the text, we present means together with their 95% CIs (in squared brackets) based on between-participants variance to give an impression of the variability of data.

2.2.1 DIRECT TEST

In the direct test, a *hit* was defined as the correct detection of a change; a *false alarm* was defined as incorrect change detection in no-change trials (i.e., same condition). *Table 1* shows mean *Pr* scores across conditions dependent on age.

Performance in the new shape and new color conditions was averaged to obtain a composite index of item memory. Item memory was contrasted with performance in the recombination condition—which provided an index of binding memory—in a 2 × 2 × 2 mixed-measures analysis of variance (ANOVA) with within-subjects factors stimulus type (extrinsic, intrinsic) and change type (item [i.e., new shape/new color], binding [i.e., recombination]), and the between subjects factor age group (young, old). Results are displayed in *Figure 2*.

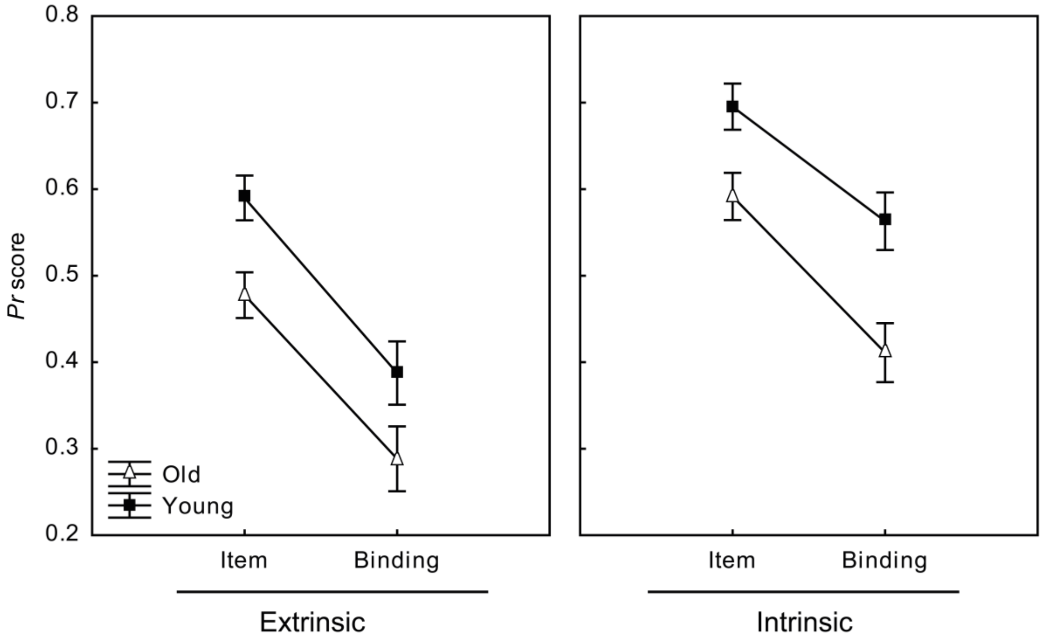

Figure 2: Corrected recognition scores (*Pr*) for older and younger participants in the direct test. Performance is depicted for item changes (aggregated across new color/new shape changes) and binding changes (recombinations) across stimulus types (extrinsic, intrinsic). Error bars show 95% confidence intervals of means based on ipsative residuals (following Cousineau, 2005).

The analysis yielded a main effect of stimulus type: memory performance was greater for intrinsic stimuli, *M* = .57, 95% CI [.54, .59], *SE* = .01, compared to extrinsic stimuli, *M* = .44, 95% CI [.41, .47], *SE* = .015, with *F*(1, 86) = 71.57, *p* < .001, η_p^2 = .45. There was also a main effect of change type: detection of shape-color recombinations, *M* = .41, 95% CI [.38, .44], *SE* = .016, was lower than detection of item changes (i.e., new shape or new color), *M* = .59, 95% CI [.57, .61], *SE* = .011, with *F*(1, 86) = 215.96, *p* < .001, η_p^2 = .72. These main effects were qualified by a marginal interaction between stimulus type and change type, with *F*(1, 86) = 3.28, *p* = .074, η_p^2 = .04. The main effect of age was also significant: older participants, *M* = .44, 95% CI [.41, .48], *SE* = .017, performed worse than younger participants, *M* = .56, 95% CI [.53, .59], *SE* = .017, with *F*(1, 86) = 23.17, *p* < .001 η_p^2 = .21. There were no two-way interactions involving age (all *F* < 1), and the three-way interaction was also non-significant, with *F*(1, 86) = 1.99, *p* = .16, η_p^2 = .02. In sum, results demonstrated generally reduced recognition performance for extrinsic (as compared to intrinsic) stimuli and a general impairment arising with age. There was, however, no indication of an age-related binding deficit in WM, neither for intrinsic nor for extrinsic stimuli[3].

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[3] To exclude the possibility that different trial numbers across feature and recombination conditions influenced the results, we repeated the analysis with change type as a three-level factor (new color, new shape, recombination); in this analysis, all conditions have the same number of trials. The analysis revealed the same two main effects as the combined analysis.

Table 1: Recognition performance scores (*Pr*) for older and younger participants in the direct association WM test of Experiment 1

Age group	**Stimulus type**	**Change type**	***Pr***	**(*SD*)**
Young	Extrinsic	New shape	0.56	(.12)
		New color	0.62	(.14)
		Recombined	0.39	(.19)
	Intrinsic	New shape	0.68	(.12)
		New color	0.71	(.17)
		Recombined	0.56	(.16)
Old	Extrinsic	New shape	0.44	(.16)
		New color	0.52	(.19)
		Recombined	0.29	(.19)
	Intrinsic	New shape	0.52	(.15)
		New color	0.66	(.15)
		Recombined	0.41	(.18)

Note. *Pr* = Mean corrected recognition scores; *SD* = Standard deviation.

Additionally, we analyzed item memory separately for shape and color change conditions (see *Figure 3*). To this end, we ran a 2 × 2 × 2 mixed-measures ANOVA with within-subjects factors stimulus type (extrinsic, intrinsic) and change type (new shape, new color), and the between-subjects factor age (young, old). Apart from effects already demonstrated in the previous analysis, this analysis yielded a main effect of change type: new color changes, M = .63, 95% CI [.60, .66], SE = .015, were detected more often than new shape changes, M = .55, 95% CI [.53, .57], SE = .012, with $F(1, 86) = 28.77$, $p < .001$, $\eta_p^2 = .25$. However, this main effect was qualified by a three-way interaction with stimulus type and age, with $F(1, 86) = 4.53$, $p = .036$, $\eta_p^2 = .05$. For intrinsic stimuli, the change-type effect was influenced by age, resulting in a significant interaction contrast of change type and age, with $F(1, 86) = 7.06$, $p = .009$, $\eta_p^2 = .08$. No such effect was found for extrinsic stimuli ($F < 1$). With intrinsic stimuli, relative to younger adults, older adults recognized color changes (i.e., an old shape in a new color) more often than expected and shape changes (i.e., a new shape in an old color) less often.

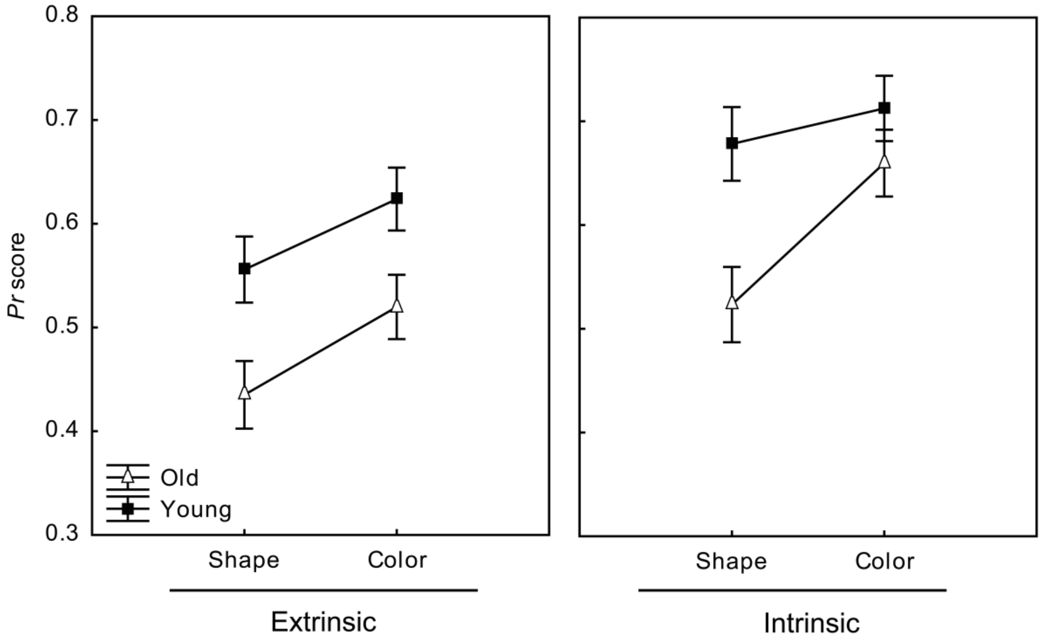

Figure 3: Corrected recognition scores (*Pr*) for older and younger participants in the direct test. Performance is depicted for item changes (new color, new shape) across stimulus types (extrinsic, intrinsic). Error bars show 95% confidence intervals of means based on ipsative residuals (following Cousineau, 2005).

2.2.2 INDIRECT TEST

In the indirect test, a “hit” was defined as the correct acceptance of a studied shape as “old”; a “false alarm” was defined as an “old” response to a new shape. Hit rates were calculated separately for the three different types of shape-matching trials (same, new color, recombined).

Table 2: Recognition performance scores (Pr) and response time (RT) costs for older and younger participants in the indirect irrelevant change WM test of Experiment 1

Age group	**Stimulus type**	**Change type**	***Pr* (*SD*)**	**RT costs (*SD*)**
Young	Extrinsic	New color	0.64 (0.17)	56 (151)
		Recombined	0.63 (0.15)	61 (143)
		No change	0.74 (0.14)	
	Intrinsic	New color	0.64 (0.18)	76 (183)
		Recombined	0.63 (0.17)	53 (135)
		No change	0.74 (0.13)	
Old	Extrinsic	New color	0.55 (0.17)	29 (179)
		Recombined	0.57 (0.14)	43 (233)
		No change	0.60 (0.17)	
	Intrinsic	New color	0.44 (0.22)	160 (267)
		Recombined	0.49 (0.17)	139 (234)
		No change	0.60 (0.15)	

Note. Pr = Mean corrected recognition scores; RT costs = response time costs (in ms).

Following ample precedent (e.g., Ecker et al., 2013; Gao et al., 2011), a secondary dependent variable in the analysis of the indirect test data was RT costs—the difference between hit RTs to unchanged same items and old items with irrelevant study-test changes. *Table 2* lists mean *Pr* scores across conditions dependent on age as well as the corresponding RT costs.

2.2.2.1 Accuracies

Pr scores were subjected to a 2 × 2 × 3 mixed-measures ANOVA with the within-subjects factors stimulus type (extrinsic, intrinsic) and change type (same, new color, recombined), and the between-subjects factor age group (young, old) (see *Figure 4*). There were main effects of stimulus type, $F(1, 86) = 8.49$, $p = .005$, $\eta_p^2 = .09$, change type, $F(2, 172) = 44.11$, $p < .001$, $\eta_p^2 = .34$, and age group, $F(1, 86) = 25.44$, $p < .001$, $\eta_p^2 = .23$. These indicated that recognition performance was better for extrinsic stimuli, $M = .63$, 95% CI [.60, .66], $SE = .014$, than intrinsic stimuli, $M = .59$, 95% CI [.56, .62], $SE = .016$, and better for same items, $M = .67$, 95% CI [.65, .70], $SE = .014$, compared to new color changes, $M = .57$, 95% CI [.53, .60], $SE = .018$, and recombined changes, $M = .59$, 95% CI [.56, .62], $SE = .014$; the latter two were not different from each other, with $p = .15$. The size of this irrelevant-change effect varied with age and stimulus type, but the corresponding pattern was observed in all simple main effects. Again, young adults, $M = .68$, 95% CI [.64, .72], $SE = .019$, generally performed better than older adults, $M = .54$, 95% CI [.50, .58], $SE = .020$.

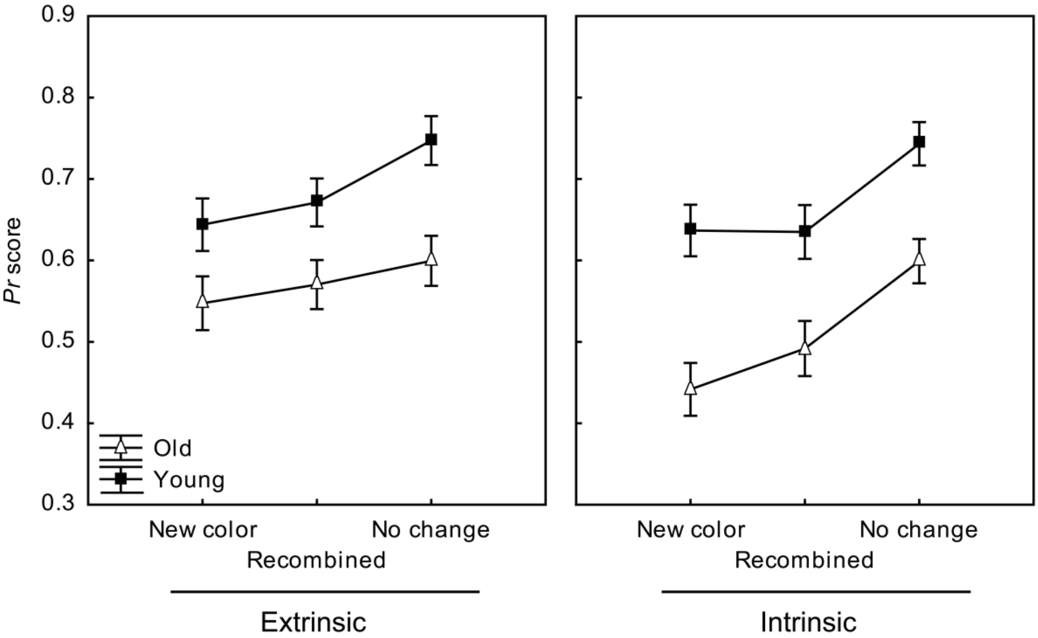

***Figure 4*:** Corrected recognitions scores (*Pr*) for older and younger participants in the indirect test. Performance is depicted for the irrelevant change conditions (new color, recombined) and the no change condition across stimulus types (extrinsic, intrinsic). Error bars show 95% confidence intervals of means based on ipsative residuals (following Cousineau, 2005).

Notably, there was a significant interaction between stimulus type and change type, $F(2, 172) = 5.24$, $p = .006$, $\eta_p^2 = .06$, which was further influenced by age, as demonstrated by a significant three-way interaction, with *F*(2, 172) = 3.44, *p* = .034, η_p^2 = .04. To better understand this interaction, we analyzed the data of the two age groups separately, in two 2 × 2 repeated measures ANOVAs with the factors stimulus type and change type. For young adults, there was only a main effect of change type, with *F*(2, 88) = 27.91, *p* < .001, η_p^2 = .39 (all other *F*s < 1). However, the corresponding analysis in older adults yielded two significant main effects [stimulus type: *F*(1, 42) = 10.43, *p* = .002, η_p^2 = .20; change type: *F*(2.84) = 18.05, *p* < .001, η_p^2 = .30], as well as a significant interaction, with *F*(2, 84) = 7.16, *p* = .001, η_p^2 = .15. Like younger adults, older adults did not show a stimulus type effect for same extrinsic, *M* = .60, 95% CI [.55, .65], *SE* = .026, and intrinsic items, *M* = .60, 95% CI [.55, .65], *SE* = .023. They did, however, show a stimulus type effect for items with task-irrelevant changes, *F*(1, 42) = 19.77, *p* < .001, η_p^2 = .32: the average recognition performance was lower for intrinsic stimuli with task-irrelevant new color changes, *M* = .44, 95% CI [.38, .51], *SE* = .033, or task-irrelevant recombination changes, *M* = .49, 95% CI [.44, .54], *SE* = .026, compared to extrinsic stimuli with task-irrelevant new color changes, *M* = .55, 95% CI [.50, .60], *SE* = .026, or task-irrelevant recombination changes, *M* = .57, 95% CI [.53, .61], *SE* = .021.

In other words, the costs of task-irrelevant change differed across the two age groups. To illustrate, *Figure 5* plots change costs, calculated as the difference between *Pr* scores for unchanged same items minus *Pr* scores for old shapes with an irrelevant color change (averaged across new color and recombined conditions). Change costs were roughly equivalent for both stimulus types in young adults; yet, in older adults, change costs were sizeable for intrinsic stimuli but small and nearly insignificant for extrinsic stimuli.

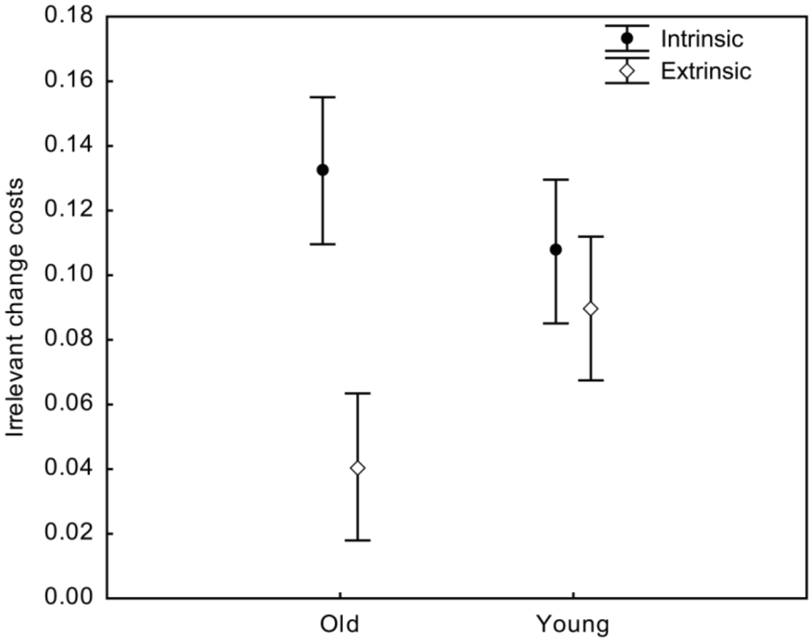

Figure 5: Recognition performance costs of irrelevant extrinsic and intrinsic feature changes for older and younger adults. Error bars show 95% confidence intervals of means based on ipsative residuals (following Cousineau, 2005).

2.2.2.2 RT costs

A pattern comparable to the results when analyzing *Pr* scores was found for RTs. Longer RTs were expected in irrelevant-change trials due to the conflict that arises from the mismatch between test probe and memory representation (e.g., Ecker et al., 2013; Gao et al., 2011). In order to estimate RT costs, RTs of the same condition were subtracted from RTs of the two irrelevant-change conditions (i.e., positive values represent costs). The log-transformed RT data were analyzed in a 2 × 2 × 2 ANOVA with within-subject factors stimulus type (extrinsic, intrinsic) and change type (new color, recombined), and the between-subjects factor age (young, old). A main effect of stimulus type was observed, $F(1, 86) = 5.20$, $p = .025$, $\eta_p^2 = .06$: RT costs were greater for intrinsic stimuli, $M = 107$ ms, 95% CI [66, 148], $SE = 21$, than extrinsic stimuli, $M = 47$ ms, 95% CI [14, 80], $SE = 17$. Although there was no significant main effect of age, with $F < 1$, there was a significant two-way interaction of stimulus type and age, $F(1, 86) = 6.47$, $p = .013$, $\eta_p^2 = .07$. Comparable to the accuracy analysis, pairwise comparisons indicated that RT costs did not differ between extrinsic, $M = 58$ ms, 95% CI [12, 105], $SE = 23$, and intrinsic stimuli, $M = 64$ ms, 95% CI [7, 121], $SE = 29$, in younger adults, $p = .85$, $d_{\text{Cohen}} = 0.03$. In contrast, older adults showed significantly greater change costs with intrinsic stimuli, $M = 150$ ms, 95% CI [91, 208], $SE = 29$, compared to extrinsic stimuli, $M = 36$ ms, 95% CI [-11, 84], $SE = 24$, $p = .001$, $d_{\text{Cohen}} = 0.50$.

2.3 DISCUSSION

The goal of Experiment 1 was twofold. The first goal was to investigate whether age has a differential influence on the intentional storage and retrieval of extrinsic and intrinsic feature bindings in WM. Binding performance was assessed in a direct test using shape-color associations in a change detection paradigm. It was assumed that an age-related binding deficit would be present for extrinsic feature associations. As expected, memory for bound extrinsic information was generally poorer than memory for bound intrinsic information. Moreover, older participants showed an overall decreased WM performance. However, contrary to expectations, there was no indication of any age-related binding deficit – neither in a general sense nor specifically for extrinsic information. The second goal was to investigate whether age affects the involuntary binding of extrinsic versus intrinsic features. Age-related binding deficits were assessed in an indirect test where the association between features was not task-relevant (i.e., an irrelevant-change paradigm). Compared to young adults, older adults were expected to show smaller costs associated with an irrelevant color change from study to test with extrinsic features but not with intrinsic features. The results clearly supported this second hypothesis.

2.3.1 PROCESSING OF EXTRINSIC AND INTRINSIC INFORMATION IN WM

Both direct and indirect tests were influenced by the type of binding, demonstrating that the distinction between intrinsic and extrinsic binding is critical not only in LTM but also in WM (see Ecker et al., 2013). Specifically, in the direct test, memory performance for intrinsic stimuli was higher than for extrinsic stimuli, as has been observed in previous work (e.g., Delvenne & Bruyer, 2004; van Geldorp et al., 2015; Walker & Cuthbert, 1998; Xu, 2002b). Interestingly, the same effect was seen in our composite index of item memory, which suggests that the advantage is not solely due to a difference in the ease of binding—it seemed generally harder to memorize features of extrinsic than intrinsic stimuli. This effect, however, was confined to the direct test: the processing advantage for intrinsic stimuli was not seen in the indirect test, where only shape information was relevant. Hence, intrinsic stimuli had an advantage over extrinsic stimuli only when both parts of the extrinsic stimuli (i.e., both the shape and the colored frame) were task relevant and had to be attended. The poorer memory performance associated with the extrinsic items is probably not a consequence of a more difficult perceptual discrimination (i.e., crowding; e.g., Whitney & Levi, 2011). It is more likely the consequence of an attentional "object benefit-like" effect: it is easier to attend to two features of the same object than attend to two features of disconnected objects (Fougnie et al., 2013; Xu, 2002b, 2002a; Xu

& Chun, 2007). This has consequences for the involuntary encoding of features, especially for elderly people, as will be discussed later.

Furthermore, in the direct test, performance in the binding condition (i.e., recombination) was generally poorer than in the item conditions (i.e., new shape/new color). Binding performance was also poorer than performance for the most difficult individual feature condition (i.e., new shape). This contradicts that complete objects are represented in memory, and that feature memory is object-based with a coarse-to-fine gradient (in which case color should have always been co-represented with shape). By contrast, the results support the assumption that features were stored separately, and that items were incompletely represented in WM (Bays et al., 2011; Cowan et al., 2013; Fougnie et al., 2013; Kursawe & Zimmer, 2015). Accordingly, recognition performance in the recombined condition was only marginally (though statistically significantly[4]; average $\Delta = .05$) better than expected based on independent feature memory (i.e., the product of the recognition probabilities for the individual features). Thus, it is possible that for the majority of items, the probability of remembering both features equates to the joint probability of sampling color and shape of the same object (Vul & Rich, 2010). Considering this, even in the binding condition, WM performance may be mainly a consequence of remembering individual features, with only a small contribution of any supplementary binding mechanism. Surprisingly, this was the case in both age groups and with both types of stimuli. We only observed a main effect of the type of stimuli, indicating that the proportion of items for which both features were remembered was clearly higher in the intrinsic than the extrinsic condition.

2.3.2 AGING AND WM PERFORMANCE

The present study replicates previous findings of a general decrease in WM performance with age. Such age effects are frequently reported across a wide range of different stimuli and tasks (for an overview, see Allen, Brown, & Niven, 2013). Causal factors that have been proposed include less efficient executive control processes as well as less distinct sensory representations in older adults (Gazzaley & Nobre, 2012). Interestingly, the results from the direct test in the present study suggest that the age-related memory impairment was present for item memory and binding conditions. As both conditions had different task

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[4] We calculated the multiplicative combination of the single-feature probabilities of new color and new shape changes for extrinsic and intrinsic stimuli. We then tested whether these values were significantly different from the obtained values in the binding conditions. The corresponding 2 × 2 × 2 ANOVA with the within-subject factors stimulus type (extrinsic, intrinsic), and value (expected, observed) and the between-subjects factor age group (young, old) only yielded a main effect of age, $F(1, 86) = 24.19$, $p < .001$, $\eta_p^2 = .22$, a main effect of stimulus type, $F(1, 86) = 72.17$, $p < .001$, $\eta_p^2 = .46$, and a main effect of value, $F(1, 86) = 18.51$, $p < .001$, $\eta_p^2 = .18$.

demands, WM impairments in the older age group seemed independent of task demands. Speculatively, it could be argued that such deficits are most plausibly explained by fluctuations in attentional control (Adam, Mance, Fukuda, & Vogel, 2015), which can lead to items being “missed” independent of task difficulty.

2.3.3 AGING AND PROCESSING OF INTRINSIC INFORMATION

The absence of an age-related binding deficit for intrinsic items was expected and replicates results from previous studies (Brockmole et al., 2008; Brockmole & Logie, 2013; Parra et al., 2009; Peterson & Naveh-Benjamin, 2016; van Geldorp et al., 2015). While the results from the direct test may not be considered strong evidence for the integrative processing of intrinsic information, more convincing evidence for integrative processing of intrinsic information is provided by the indirect test. These findings corroborate the notion that, independent of age, binding of a shape and its intrinsic surface color is a rather involuntary process (Ecker et al., 2013; Zimmer & Ecker, 2010). In fact, RT prolongations due to task-irrelevant changes to intrinsic features were approximately twice as large in older compared to younger adults; an effect observed for item and binding memory conditions. Recognition and RT effects were associated to mismatches of new information as well as recombined features to stored representations. Changes to a task-irrelevant feature did, thus, not lead to unspecific interference. In sum, the present study found no indication of an age-related binding deficit in WM for intrinsic stimuli; on the contrary, the data even suggest enhanced memory of irrelevant intrinsic information.

2.3.4 AGING AND PROCESSING OF EXTRINSIC INFORMATION

For extrinsic stimuli, no age-related binding deficit was found in the direct test. This is an unexpected result that is inconsistent with some previous research (Chen & Naveh-Benjamin, 2012; Walker & Cuthbert, 1998). The result is, however, in line with findings from recent studies that utilized a similar type-of-binding manipulation as the present study (Peterson & Naveh-Benjamin, 2016; van Geldorp et al., 2015). It seems that the spatially disjunct presentation of shape and color information in itself is not sufficient to establish an age-related association deficit in WM. Potentially, an age-related binding deficit may become apparent only when perceptual integration of the to-be-bound information is not possible even if participants know that memory of the combination is requested. For example, an age-related association deficit was found by Chen and Naveh-Benjamin (2012) with associations between faces and scenes. Faces and scenes belong to completely different domains (Mayes et al., 2007) and a face-scene binding task should, therefore, require additional processes for the association of these two perceptual units.

This might have not been the case for the extrinsic stimuli in the present study. We have already discussed that the independent encoding of color and shape from the same object can almost completely explain performance in the binding condition with both types of items. If this is correct, there is little to no supplementary binding process except for the allocation of attention to both features; this would make plausible the absence of an age-related binding deficit. Even older people should be able to perceptually group a shape and its surrounding frame if they intentionally attend to both parts of the item (for a discussion, see for example Xu, 2002b), even though this will be harder than with intrinsic items.

However, in contrast to the direct test, the indirect test results showed that the two types of stimuli were processed differently and that the two age groups differed in their ability to bind extrinsic information. In irrelevant-change conditions, a clear interaction between age and stimulus type emerged. In young participants, task-irrelevant feature changes produced equivalent performance costs with both extrinsic and intrinsic items, suggesting that the irrelevant color was represented in WM independent of item type. By contrast, older participants showed significant change costs only for intrinsic stimuli, and costs were virtually absent for extrinsic stimuli. Given the observation that older participants showed even larger change costs for intrinsic items, we interpret the absence of this effect for extrinsic stimuli as a clear indication of an age-related change in extrinsic binding.

2.3.5 CONCLUSIONS AND CAVEATS

Experiment 1 provided several clear results: (1) The distinction between intrinsic and extrinsic items is important for the understanding of binding. Extrinsic items were remembered less well than intrinsic items, both in terms of feature memory and binding memory. (2) Extrinsic items were differently processed by younger and older adults if the extrinsic feature was task-irrelevant. Both groups integrated irrelevant intrinsic information, but only young participants integrated irrelevant extrinsic information; the elderly did not do so. (3) An age-related binding deficit existed neither for spatially integrated (intrinsic) nor spatially separated (extrinsic) shape and color information if the association was intentionally encoded. (4) However, a general age-related memory deficit was observed despite our attempts to compensate for general age effects by adjusting encoding times.

The different integration of extrinsic and intrinsic information could be the result of age-related changes to early selection mechanisms when visual information is encoded into WM, or the result of changes to later binding processes when information is consolidated into WM. The paradigm utilized in Experiment 1 was not designed to distinguish between these possibilities. For this purpose, other paradigms are necessary that are sensitive to online effects of processing (see Experiments 2 and 4). In total, however, the data suggest that the age-related differences in shape-color binding were due to selection effects. In the direct test, the stimulus and age effects were visible in feature memory as well as in binding memory, and the effects were similar for both types of stimuli. We have no evidence for a substantial binding process other than the joint encoding of color and shape features (see also Vul & Rich, 2010). The same mechanism might explain the difference in the indirect test: If younger but not older participants attended to the irrelevant extrinsic color information, only the younger participants would represent the surrounding color in the object file representing the item. Cowan and colleagues have suggested that unitized objects and feature representations can coexist in WM and that the task demands influence which representation drives the observed effects (Cowan et al., 2013; Vergauwe & Cowan, 2015). The present results demonstrate that the type of stimulus (extrinsic vs. intrinsic) and participants' age are further variables that need to be considered in models of information integration in WM.

Given the results from Ecker et al. (2013), the virtually equivalent costs for task-irrelevant extrinsic and intrinsic feature changes in younger adults were surprising. We can only speculate about the reasons for this difference. One relevant factor might lie in the extrinsic stimuli's composition. The items in the study of Ecker and colleagues were three-dimensional shapes that were superimposed on squares, with color manipulated as a foreground feature of the shape or a feature of the background square. In order to perceive the shape, the figure must be separated from the ground (see Peterson & Kimchi, 2013, for a review). If attention is oriented to the foreground it cannot be oriented at the same time to the background. This would make it less likely to encode the irrelevant extrinsic color together with the shape. Potentially, this hindered processing of background color and consequentially impaired memory for it.

Furthermore, due to the numerous potential moderators of the binding effect, age-related influences on binding should be investigated with other paradigms and materials. For example, an obvious difference to previous studies is that our encoding times were individually estimated (see Appendix 1). Therefore, the presentation times of the study display were longer than usual (e.g., Gao et al., 2011; Luck & Vogel, 1997; Xu, 2002b). Our results were similar to those of Peterson and Naveh-Benjamin (2016), who used shorter encoding times, and those of van Geldorp et al. (2015), who used longer encoding times. The same independence of encoding time was found for intrinsic stimuli (Brown et al., 2017; Rhodes et al., 2016). For this reason, encoding time does not seem critical for the absence of the age-related binding deficit in the direct test of our study. However, if shape-color binding is a byproduct of feature encoding with both types of stimuli, encoding time should not influence performance provided it is sufficiently long to allow feature encoding, as no additional time-consuming binding processes are performed. This may be different if other types of information have to be associated which require additional binding processes beyond simultaneous feature encoding. If these processes are time-consuming, binding should only be possible with long but not short encoding times (e.g., Rhodes et al., 2016) and the effect of encoding time may even become stronger with advancing age (Rhodes et al., 2016; Rhodes et al., 2017). This aspect is dealt with in Experiment 2.

Finally, an open issue is how the test procedure might influence participants' cognitive processing. We used a single test probe to focus on object-feature bindings and eliminate the influence of object-location bindings (Cowan et al., 2013). Participants were asked to decide whether the single test item matched their memory representation. It is unknown whether this similarity-driven comparison is identical to processing in a whole-report change detection task. It is assumed that in the whole-report task, participants initially perform a parallel search for differences and subsequently engage in a conditional evaluation of the critical, potentially deviant item (Hyun et al., 2009). This secondary evaluation process appears similar to the evaluation of a single test probe. However, the evaluation of a single probe may have a stronger focus on detecting "sameness" (i.e., a match with the memory representation), whereas the secondary evaluation in a whole-report task may have a stronger focus on detecting a difference (i.e., a mismatch). We are not aware of any study that has tested this assumption directly; this thus remains a target for future research.

3 EXPERIMENT 2: AGE-RELATED CHANGES TO ENCODING INTRINSIC AND EXTRINSIC FEATURES INTO WM.

The first study yielded indications that intrinsic and extrinsic information are processed differently by younger and older adults. If not intentionally heeded, older adults appeared to retain extrinsic information in visual WM to a less extent than younger adults. If older adults, however, intentionally directed their attention toward intrinsic or extrinsic information, no difference was found for storing different types of visual information. Differences in extrinsic binding performance might, thus, not be apparent under all task conditions. Most notably, in the first experiment, the time given to encode the stimuli was individually adjusted for each participant to minimize any effect associated to visual information processing. This manipulation may have caused differences in the intentional encoding demands of intrinsic and extrinsic features to become unobservable, as indicated by the difference between intentional and unintentional encoding conditions (direct/indirect test).

Experiment 2, therefore, investigates the role of binding processes for the consolidation of object-feature associations into WM. If binding of intrinsic features is a byproduct of visual encoding, the time available to process the visual information should not influence performance provided it is sufficiently long to allow perceptual feature encoding. In contrast, according to the type-token model (Zimmer & Ecker, 2010), associating extrinsic types of visual information is assumed to require binding processes beyond mere feature encoding in WM (Delvenne & Bruyer, 2004). Thus, the presence (or absence) of increased processing demands for extrinsic bindings could depend significantly more on the time available to transfer the information into WM than for intrinsic bindings (for a comparable discussion, see Rhodes et al., 2017). Moreover, the influence of encoding time should be even more pronounced with increasing age (Rhodes et al., 2016; Rhodes et al., 2017), if age-related deterioration influences affect information processing (e.g., Fjell & Walhovd, 2010).

3.1 ENCODING TIME AND WM

Besides the amount of information that can be retained, WM limitations could manifest at other stages. Evidence from different research paradigms indicate that the process engaged to transfer information into (visual) WM is another factor (e.g., Enns & Di Lollo, 2016; Jolicœur & Dell'Acqua, 1998; Vogel et al., 2006). Vogel et al. (2006) suggested that—in addition to mere perceptual encoding—time is necessary to consolidate a representation in WM. The term “consolidation” refers to the process that transfers “*a fleeting perceptual representation into a durable WM representation that can survive the presentation of new sensory inputs*” (Vogel et al., 2006, p. 1436). For example, if conflicting information is shown at a location where the task-relevant information was presented shortly before, memory performance for the to-be-remembered information is significantly impaired even if sufficient perceptual encoding was possible (see, e.g., Sun, Zimmer, & Fu, 2011). Here, we refer to encoding as a process that transfers the quality of a perceptual representation into a durable WM representation that follows perceptual encoding.

To investigate the time course of transferring a visual percept into a stable WM representation, Vogel et al. (2006) utilized an adaption of the change detection paradigm where they systematically terminated the time available to process the visual information. In their study, participants solved a change detection task where they indicated whether stimuli presented during a first memory array were same or changed at a second presentation after a short delay of 900 ms. The memory array consisted of a small number of color patches. The colors were presented for 100 ms to allow sufficient perceptual processing (see, e.g., Luck & Vogel, 1997, where participants performed near ceiling with this presentation time if WM capacity was not exhausted). Critically, when the to-be-remembered stimuli disappeared, irregular color-pattern masks where presented for 200 ms during the delay interval at the same locations as the task-relevant stimuli (for a comparable paradigm, see Sun et al., 2011). Masking is argued to cancel the possibility to further mentally process the visual information, even if the information is no longer available (Gegenfurtner & Sperling, 1993). Presenting masks thus restricts the time to process the information to the stimulus onset asynchrony (SOA) between the onset of the memory array and the onset of the masks. Vogel and colleagues (2006) systematically varied the time interval between the disappearance of the memory array and the onset of the masks from 17 ms to 484 ms. If participants had to store a number below the estimated WM capacity, memory performance gradually increased as SOA increased. This suggests that encoding more information in WM consumes more time. Further, Vogel et al. (2006) argued that this result was not due to the mask influencing perceptual processing, as the authors did not find visual search to be influenced by masks nor did pre-exposing the mask to the memory array influence the memory performance. Other studies systematically manipulated the presentation time of the to-be-remembered items, instead of holding the presentation time of the stimuli constant and varying the time elapsed until the masks are shown. In these studies, the masking display immediately replaced the memory array (e.g., Gao et al., 2011).

The time needed to safely encode information into WM does not seem to be a constant variable. Time requirements can vary with the format of the visual information: Woodman and Vogel (2008) found that the encoding of color progresses on a significantly faster rate than shape or orientation. Similarly, Gao and colleagues (2011, Experiment 5) reported faster encoding of basic features, such as colors, compared to complex features, such as the orientation of a gap (but see Sun et al., 2011, Experiment 5). Interestingly, Woodman and Vogel (2008) found that—compared to trials with only a single task-relevant object feature—the encoding rate of multiple-feature associations was not slower than the rate for the slower to encode single feature (i.e., encoding of shape-color combinations was not significantly different from encoding only the shape feature, while both differed from encoding the color feature). In sum, these results suggest that the visual material influences the consolidation of the corresponding information into WM.

In the present Experiment 2, we focus on whether the type of binding required influences the consolidation of the object. Woodman and Vogel (2008) focused on the comparison between storing single and multiple features of to-be-remembered objects. Their results yielded no costs for storing more features within an object representation. However, at test, participants could detect a change by recognizing one of the features as "new". No strict binding test condition was administered. We argue that different binding mechanisms exist to process intrinsic and extrinsic feature associations (Ecker et al., 2013; Zimmer & Ecker, 2010). While the former binding mechanism is thought to function rather automatically or cost-free, the latter is thought to be more deliberate and supplementary. In line with this assumption, Delvenne and Bruyer (2004) found RT latencies to increase if extrinsic compared to intrinsic shape-texture association had to be processed in a change detection task. The authors argued that these increased demands on RTs could reflect the need for additional or even subsequent cognitive mechanisms. Hence, the difference between intrinsic and extrinsic stimuli could influence the consolidation process of the corresponding binding information.

3.2 ENCODING TIME AND AGE

The masked change detection paradigm might also be suited to investigate whether the lack of an age-related binding deficit for intentionally encoded bound information was due to the individually adjusted encoding time (Experiment 1). Increased encoding times could have encouraged more elaborate processing strategies. Increasing the time in parallel with the cue to intentionally store the association could have, thus, encouraged older adults to compensate for age-related changes.

Age-related changes to binding performance could, therefore, be more pronounced under conditions with shorter encoding times (for a similar discussion, see Rhodes et al., 2017). For example, Rhodes et al. (2016) investigated the role of encoding time in older and younger adults. The authors compared the effects of longer (2500 ms) and shorter (900 ms) presentation times for feature and binding memory for intrinsic stimuli. They found no indications that increasing the presentation time of the memoranda influenced WM performance for younger or older adults. Moreover, no disproportionate effect was found for binding memory. Similar results were obtained by Brown et al. (2017) with 1500 ms and 900 ms of presentation time. Again, older adults binding performance was not influenced by encoding time. However, both studies used intrinsic stimuli and fairly large differences between presentation times. In addition, the lack of masking stimuli could have further lengthened the time available to consolidate the information beyond mere presentation time (Vogel et al., 2006). Thus, data about age-related changes to the consolidation of intrinsic bindings is far from being conclusive whilst there is almost no information available for extrinsic binding.

Experiment 2 is aimed to test whether the time available to transfer a percept into a stable WM representation affects intrinsic and extrinsic binding differently. If extrinsic binding is a supplementary process that has to be intentionally engaged, this could be time-consuming. We thus expected that the consolidation of extrinsic bindings to be more closely related to the time available than intrinsic bindings. If extrinsic binding is especially prone to age-related changes in hippocampal functioning, we would expect that WM performance impairments should be even more pronounced for older adults and shorter presentation times. In contrast, we would expect that the consolidation of intrinsic stimuli is not differentially impaired at old age.

To test these hypotheses, older and younger participants solved a masked change detection paradigm. To estimate sufficient perceptual encoding (Vogel et al., 2006), prior to varying the presentation time, participants solved a pretest with a smaller set size (see Chapter 3.3.3 for details). Intrinsic and extrinsic shape-color associations were presented for different durations and consolidation was terminated by mask presentation. Participants were instructed to indicate whether a change happened from study to test. Similar to Experiment 1, this could either be a feature change, where a new color or shape information is presented at test, or it could be a feature recombination change, requesting the representation of correct bindings. Again, a single test probe was presented in a central location to minimize the necessity to store object-location bindings (Cowan et al., 2013; van Geldorp et al., 2015).

3.3 METHODS

The experiment used a fully crossed 4 (SOA: very short, short, long, very long) × 2 (stimulus type: intrinsic, extrinsic) × 4 (change type: same, new shape, new color, recombined) × 2 (age: young, old) mixed design, with age as the only between-subjects factor.

3.3.1 PARTICIPANTS

A total of 95 participants took part in the study; 53 were young adults (undergraduate students from Saarland University) and 42 were older adults. Experimental data from eight younger participants could not be evaluated due to technical issues. One younger and two older participants did not complete the experiment, and three younger participants reported health issues. Data from these participants was excluded, so that the final sample size was $N = 81$, comprising of $n = 41$ young adults (age range 18–30 years; mean age $M = 21.88$, $SD = 2.98$; 34 women, 7 men) and $n = 40$ older adults (age range 63–82 years; mean age $M = 70.12$, $SD = 4.89$; 23 women, 17 men).

All participants reported good health, normal or corrected-to-normal vision, no history of neurological disorders (in the last 5 years), and no use of medication that might influence RTs. Older adults additionally solved the Montreal cognitive assessment, a brief screening tool for mild cognitive impairments (Nasreddine et al., 2005). The mean score was $M = 27.36$ ($SD = 1.99$), suggesting no major cognitive impairments in the older sample. All participants provided written informed consent after reading an ethically approved information sheet; they received a monetary compensation of €8 per hour. The study was performed under ethical approval of the Ethics Committee of the Philosophical Faculty III Empirical Human Sciences at Saarland University.

Participants' processing speed was assessed with a digit symbol substitution test adapted from Wechsler (2008). Younger participants' mean score was $M = 69.91$ ($SD = 7.99$), older participants' mean score was $M = 50.11$ ($SD = 9.11$). Both values are in a similar range as in Experiment 1. The domain of crystallized intelligence was assessed by the multiple-choice knowledge test adapted from Lehrl (1977). Younger participants' mean score was $M = 28.98$ ($SD = 2.91$), whereas older participants' mean score was $M = 33.22$ ($SD = 1.87$).

3.3.2 MATERIALS AND APPARATUS

A set of nine geometric shapes was used throughout the whole experiment. Simple shapes were chosen to reduce age-related visual processing deficits due to stimulus complexity (Faubert, 2002). Each shape was encased with a spatially separated quadratic frame. Two versions of the stimuli were generated: for intrinsic stimuli, the shape was fully colored and the frame was always white (RGB values in parentheses; 255, 255, 255); for extrinsic stimuli, the shape was always white and the frame was colored. Thus, intrinsic and extrinsic shape-color combinations were structurally identical, with only color changing its distribution from either being inherent to the shape (intrinsic condition) or integrated into the frame disjunct from the shape (extrinsic condition). The eight discriminable colors used were blue (45, 79, 144), cyan (106, 198, 217), green (58, 170, 53), yellow (241, 230, 13), red (229, 28, 32), purple (200, 82, 155), brown (183, 103, 60), and rose (255, 198, 198). All stimuli were presented on a grey (128, 128, 128) background. The shapes subtended 1.14° × 1.14° of visual angle. The surrounding frame subtended 1.82° × 1.82° of visual angle. The width of the frame was 0.13° of visual angle, thus creating a spatial separation between shape and frame. As similarity to the memorandum influences the efficiency with which a mask can terminate the consolidation of the previous stimuli (Blalock, 2013), masks were based on the visual components of the memoranda: First, nine images were created by combining all nine shapes used in the experiment, with each shape being presented in one of the eight colors or white. Each of the nine pictures involved other color-shape pairings. The pictures subtended 1.82° × 1.82° of visual angle. To create the final mask stimuli, each picture was randomly scrambled on the basis of squares subtending approximately 0.30° × 0.30° of visual angle, thus creating nine different mask stimuli that incorporate the characteristics of the stimuli used. The experimental procedure was presented on a 23-inch flat-screen monitor with a resolution of 1,920 × 1,080 pixel and a refresh rate of 60 Hz. Participants were seated at an approximate viewing distance of 60 cm.

3.3.3 PROCEDURE

3.3.3.1 Pretest: 2-stimuli change detection task

Appropriate minimal exposure duration for the memory array of the main task was estimated in a 2-stimuli change detection task pretest (see Wiegand et al., 2014). To this end, the exposure duration with which a participant could solve two blocks of a masked change detection task with two intrinsic stimuli with an accuracy of at least 9|12 correct trials each was chosen as the basis for the exposure durations of the main 3-stimuli masked change detection task.

The trial structure of the 2-stimuli change detection task pretest is presented in *Figure 6*. Each pretest trial began with the presentation of a central fixation cross. After 400 to 600 ms (the exact interval was randomly determined), the memory array appeared, consisting of two intrinsic stimuli randomly presented on an invisible circle subtending 6° of visual angle, with the restriction that the center points of the stimuli were at least 3° of visual angle apart from each other. The initial exposure duration for the memory array was 100 ms. Each stimulus consisted of a different color and shape, with no repetition allowed within the memory array. The memory array was terminated by the presentation of a masking display for 200 ms. After a delay of 800 ms (resulting in a WM retention interval of 1,000 ms), a single probe stimulus was presented at the center of the screen, a location never occupied by any stimulus during the study phase. Participants indicated via button press on a Cedrus response pad (RB-834, Cedrus Corporation, San Pedro, California, USA) whether the probe stimulus matched one of the studied stimuli. Response categories (match/nonmatch) were assigned to the response buttons in counterbalanced order across subjects. The probe stimulus remained until a response was captured or for a maximum of 3,000 ms. It was followed by an inter-trial interval of 600 ms. Both accuracy and response speed were emphasized.

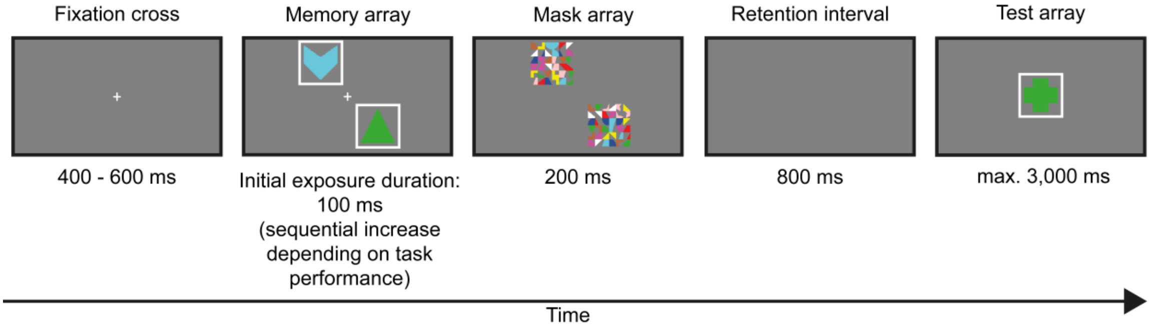

Figure 6: Schematic illustration of the trial structure of the pretest of Experiment 2, the 2-stimuli change detection task, not drawn to scale. In the example, a new-shape change is depicted (i.e., the test probe is presented in a known color paired with a new shape not presented in the memory array). For details to exposure durations, see Procedure section in Chapter 3.3.3.1.

The appropriate presentation time was determined consecutively in blocks of 12 trials each. Half the trials (6) were matching trials, the other half were nonmatch trials that were divided in shape-change (3) and color-changes trials (3). If a first block was solved with an accuracy of at least 9|12 correct trials, participants encountered another block with the same exposure duration to repeat the performance. If a participant failed to meet the accuracy criterion, the presentation time was increased by 100 ms in the next block. If participants met or exceeded the accuracy criterion a second time, this exposure duration was chosen to calculate the exposure duration for the 3-stimuli masked change detection task. An example of the algorithm can be found in *Figure 7*. To ensure adequate understanding of the paradigm, participants solved 12 practice trials, which were not included in analyses.

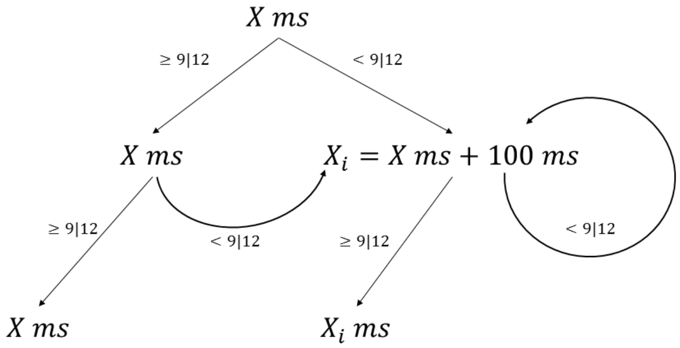

Figure 7: An example of the estimation of appropriate presentation times in the pretest of Experiment 2. Each participant started with the presentation duration of X ms. If the participant solved at least 9|12 trials correctly, the same presentation time of X ms was presented again. If the participant solved at least 9|12 trials correctly for a second time, X ms was the basis for the calculation of the presentation times in the main task. If a participant did not manage to solve 9|12 trials correctly, presentation time was increased in steps of 100 ms and the algorithm continued.

To provoke a broad range of task demands, four different exposure durations were created for the main task based on the presentation time (*T*) derived from the pretest: very short (*T – 50 ms*), short (*T + 50 ms*), long (*T + 150 ms*), and very long (*T + 500 ms*). These exposure durations were then used in the main task. The frequencies of the SOAs obtained by the pretest can be found in *Table 3*.

Table 3: SOAs obtained for each encoding condition in the main task of Experiment 2 (very short, short, long, very long) displayed in ms

SOAs				**Younger adults frequency**	**Older adults frequency**
Very short	**Short**	**Long**	**Very long**		
50	150	250	600	24	1
150	250	350	700	16	11
250	350	450	800	0	15
350	450	550	900	0	8
450	550	650	1000	1	4
550	650	750	1100	0	1

Note. SOA = stimulus onset asynchrony.

3.3.3.2 Main task: 3-stimuli change detection task

The trial structure of the 3-stimuli change detection main task is presented in *Figure 8*. Procedure was similar to the pretest 2-stimuli change detection task with the following exceptions: a) intrinsic and extrinsic stimuli were presented, b) three stimuli were presented during the memory array, hence, under very short exposure duration, adequate perceptual encoding should be minimized, c) three masks were presented to accommodate the increase in to-be-remembered stimuli, d) recombination changes were additionally possible during the test phase, and e) the presentation time of the memory array was fixed based on the results from the pretest and varied according to the scheme outlined.

There were a total of 640 trials; half of these (320) presented intrinsic and half extrinsic stimuli. The trials of each stimulus type were divided a quarter each into different SOAs for very short (80), short, long, and very long exposure durations of the study array. For each exposure duration, half the trials (40) required no-change responses, and half required change responses. Changes were subdivided in half recombination changes (20) and new-feature changes (20), while new-feature changes consisted to equal parts of color- and shape-changes (10 trials each). Trials were in random order. Every 40 trials, participants could take a self-paced break. To ensure adequate understanding of the paradigm, there were 24 practice trials which were not included in the data analyses. Experiment 2 lasted 1 to 1.5 hours.

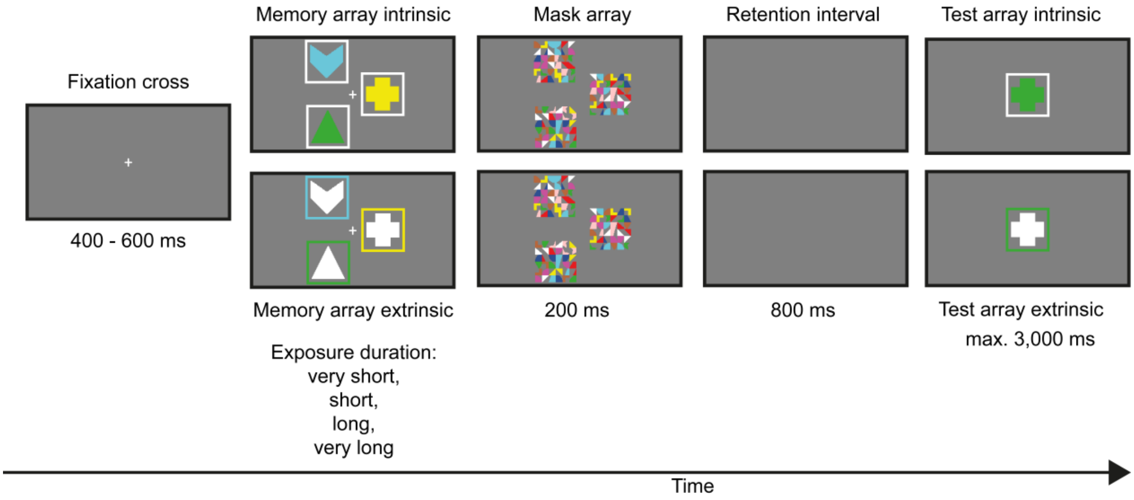

Figure 8: Schematic illustration of the trial structure of the main task of Experiment 2, the 3-stimuli change detection task, not drawn to scale. In the example, a recombination change is depicted (i.e., the test probe is a shape previously paired with another color from the memory array). For details to exposure durations, see procedure section in Chapter 3.3.3.2.

3.4 RESULTS

A trial exclusion procedure similar to Experiment 1 resulted in the exclusion of 3.23% of the trial data (Hoaglin et al., 1986; Hoaglin & Iglewicz, 1987). The dependent variable accuracy was scored as corrected recognition *Pr* scores (see Experiment 1): A “hit” was defined as the detection of a change, a “false alarm” was defined as the incorrect indication that a change happened during a no-change trial. Similar to Experiment 1, performance in the new-color change and the new-shape change condition was averaged to a composite index for item memory that can then be compared to memory for bound features (i.e., recombination changes). In the figures, we present 95% CIs based on within-subjects variances to make a direct comparison of conditions possible if adequate (following Cousineau, 2005). If homogeneity of variances was violated during statistical analyses, Greenhouse-Geisser-corrected degrees of freedom are reported. Follow-up analyses using pairwise comparisons were Bonferroni-corrected if needed, as indicated by the subscript. In the text, we present means together with their 95% CIs (in squared brackets) based on between-participants variance to give an impression of the variability of data. *Table 4* shows mean *Pr* scores across conditions depending on the age group.

Table 4: Recognition performance scores (*Pr*) for older and younger participants in the main 3-stimulus change detection task in Experiment 2

Age group	**Stimulus type**	**Change type**	**SOA**			
			$Pr_{\text{very short}}$	Pr_{short}	Pr_{long}	$Pr_{\text{very long}}$
Young	Intrinsic	Color	0.37	0.54	0.57	0.66
		Shape	0.19	0.39	0.42	0.50
		Recombined	0.17	0.36	0.43	0.43
	Extrinsic	Color	0.33	0.47	0.50	0.58
		Shape	0.18	0.30	0.32	0.42
		Recombined	0.18	0.34	0.33	0.34
Old	Intrinsic	Color	0.36	0.38	0.44	0.57
		Shape	0.23	0.24	0.28	0.38
		Recombined	0.22	0.26	0.27	0.32
	Extrinsic	Color	0.27	0.26	0.31	0.38
		Shape	0.21	0.22	0.23	0.33
		Recombined	0.16	0.18	0.22	0.23

Note. SOA = Stimulus onset asynchrony; Pr_X = mean corrected recognition scores with indices for SOA durations. All standard deviations for *Pr* scores ranged between 0.02 and 0.04.

We first tested whether the estimation of the shortest exposure duration produced insufficient perceptual processing for both age groups. To this end, item and binding memory were compared in a 4 × 2 × 2 × 2 mixed-measures ANOVA with within-subjects factors SOA (very short, short, long, very long), stimulus type (extrinsic, intrinsic) and change type (item [i.e., new shape/new color], binding [i.e., recombination]), and the between-subjects factor age (young, old). If the manipulation was sufficient, the two groups should not differ at the level of the shortest exposure duration. The analysis yielded a main effect of stimulus type $F(1, 79) = 72.23$, $p < .001$, $\eta_p^2 = .48$, change type, $F(1, 79) = 152.81$, $p < .001$, $\eta_p^2 = .66$, and SOA, $F(3, 237) = 70.48$, $p < .001$, $\eta_p^2 = .47$, that were qualified by two two-way interactions with factor stimulus type and SOA, $F(3, 237) = 2.69$, $p = .047$, $\eta_p^2 = .03$, and change type and SOA, $F(3, 237) = 13.57$, $p < .001$, $\eta_p^2 = .15$. There was a significant main effect of age group, $F(1, 79) = 14.07$, $p < .001$, $\eta_p^2 = .15$, and this effect was qualified by a significant interaction with SOA, $F(3, 237) = 14.36$, $p < .001$, $\eta_p^2 = .15$. There were no other significant interactions, with the smallest *p*-value for the interaction of stimulus type, SOA, change type, and age group, $F(3, 237) = 1.95$, $p = .12$, $\eta_p^2 = .02$. Pairwise comparisons of the two groups indicated, that memory performance of older and younger participants did not differ for very short exposure durations ($p = .84$) but for all longer exposure durations (all *p*s < .003). This indicates that older and younger adults did not differ if insufficient time was given to perceptually process the memoranda (see *Figure 9*), suggesting a sufficient manipulation of presentation time. We thus excluded memory performance for the shortest exposure duration from following analyses.

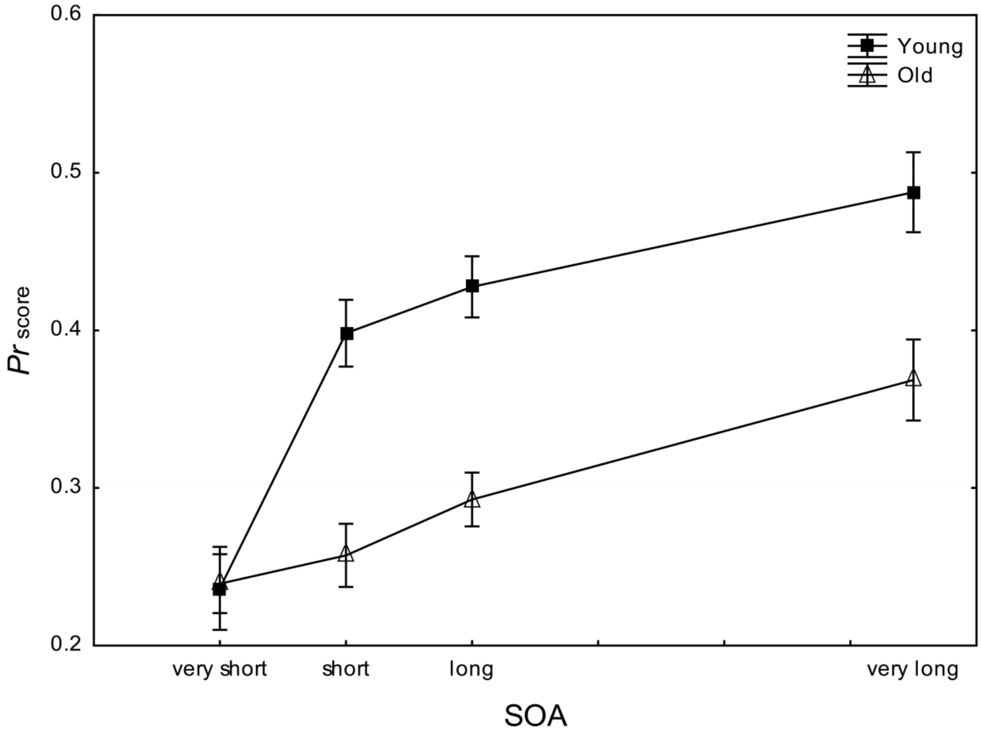

Figure 9: Corrected recognition scores (*Pr*) for older and younger participants in the main task. Performance is depicted for each estimated SOA (aggregated across all stimulus and change types). Error bars show 95% confidence intervals of means based on ipsative residuals (following Cousineau, 2005).

Item and binding memory were compared in a 3 × 2 × 2 × 2 mixed-measures ANOVA with within-subjects factors SOA (short, long, very long), stimulus type (extrinsic, intrinsic) and change type (item [i.e., new shape/new color], binding [i.e., recombination]), and the between subjects factor age (young, old). The analysis yielded a significant main effect of age, *F*(1, 79) = 22.21, $p < .001$, $\eta_p^2 = .22$, with older adults, *M* = .29, 95% CI [.25, .33], *SE* = .02, performing overall worse than younger adults, *M* = .42, 95% CI [.38, .46], *SE* = .02; a main effect of stimulus type, *F*(1, 79) = 93.95, $p < .001$, $\eta_p^2 = .54$, with performance being overall lower for extrinsic, *M* = .32, 95% CI [.29, .34], *SE* = .01, compared to intrinsic stimuli, *M* = .40, 95% CI [.37, .43], *SE* = .02; a main effect of SOA, *F*(1.86, 146.68) = 25.47, $p < .001$, $\eta_p^2 = .24$, with pairwise comparisons indicated that memory performance increased as exposure duration increased (short: *M* = .32, 95% CI [.29, .35], *SE* = .02; long: *M* = .35, 95% CI [.32, .38], *SE* = .01; very long: *M* = .40, 95% CI [.37, .44], *SE* = .02; with all *p*s < .008); and a main effect of change type, *F*(1.86, 146.68) = 128.17, $p < .001$, $\eta_p^2 = .62$, with memory for recombined items, *M* = .31, 95% CI [.28, .34], *SE* = .01, being overall worse than memory for single feature tests, *M* = .40, 95% CI [.38, .43], *SE* = .01. There was a significant interaction of SOA and change type, *F*(2, 158) = 17.07, $p < .001$, $\eta_p^2 = .18$, while no other interaction reached significance, with the smallest *p*-value for the four-way interaction of SOA, stimulus type, change type and age-group approaching the conventional level of significance, $F(2, 158) = 2.44$, $p = .09$, $\eta_p^2 = .03$.

The interaction of SOA and change type was further investigated (see *Figure 10*): Planned pairwise comparisons revealed that memory performance increased from short to very long SOAs for item memory (short: $M = .35$, 95% CI [.32, .38], $SE = .02$; long: $M = .38$, 95% CI [.35, .41], $SE = .02$; very long: $M = .48$, 95% CI [.44, .51], $SE = .02$; with the largest $p = .001$), while memory performance for bound information increased from short to long SOAs, $p = .04$, but did not increase from long to very long SOA, $p = .22$ (short: $M = .29$, 95% CI [.26, .32], $SE = .02$; long: $M = .31$, 95% CI [.29, .34], $SE = .01$; very long: $M = .33$, 95% CI [.29, .37], $SE = .02$). Overall, the analysis indicated that the exposure duration did not differentially affect older and younger participants' memory performance, neither for intrinsic, nor extrinsic stimuli. However, feature memory benefited from longer presentation times, while memory for bound information reached an earlier plateau.

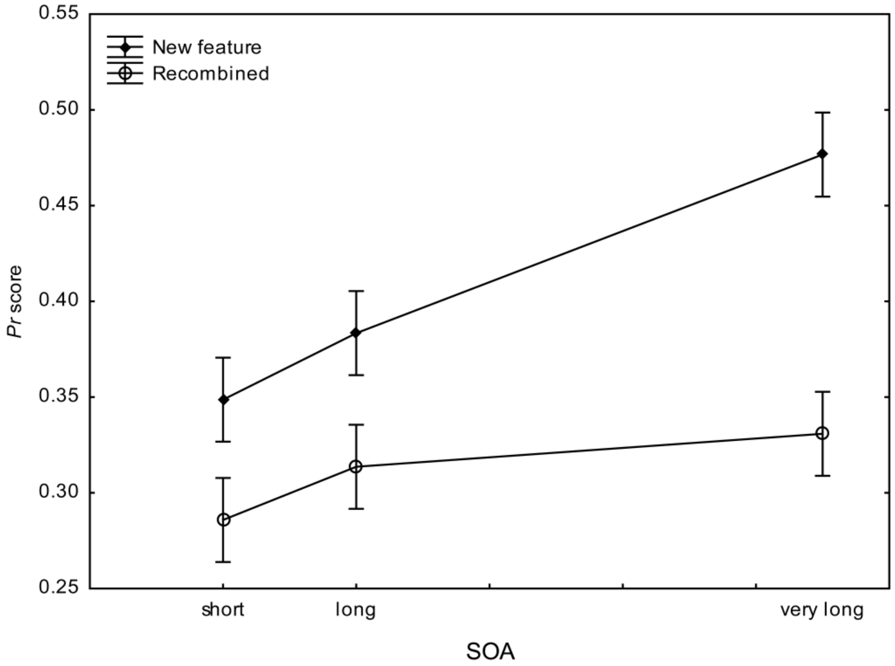

Figure 10: Corrected recognition scores (*Pr*) for trials with new feature changes (new shape/new color) and recombination changes in the main task. Performance is depicted for each SOA (aggregated across age groups and stimulus types). Whiskers show 95% within-CIs for the means corrected according to Jarmasz and Hollands (2009).

To further investigate whether binding performance might be equivalent to the performance for the slowest-to-consolidate feature (see Woodman & Vogel, 2008), we repeated the analysis with separated item memory for color and shape changes in a 2 × 3 × 3 × 2 mixed-measures ANOVA, with factors stimulus type (intrinsic, extrinsic), SOA (short, long, very long), change type (new color, new shape, recombined), and the between-subjects factor age group (young, old). Besides the known main effects of age group, stimulus type, SOA, and change type, and the known interaction of SOA and change type from the previous analysis, there were significant interactions of change type and age group, $F(2, 158) = 3.59$, $p = .030$, $\eta_p^2 = .04$, as well as stimulus type and change type, $F(2, 158) = 4.41$, $p = .014$, $\eta_p^2 = .05$. The latter two interactions were further qualified by a significant three-way interaction of stimulus type, change type, and age group, $F(2, 158) = 7.24$, $p = .001$, $\eta_p^2 = .08$ (see below). The analysis yielded no indications that SOA differentially influenced the processing of intrinsic and extrinsic information, neither for younger, nor older adults (see *Figure 11*). This was found for item and binding memory performance. This suggests that the time available to process the information did not differentially influence WM performance for intrinsic and extrinsic bound features. This was found across both age groups.

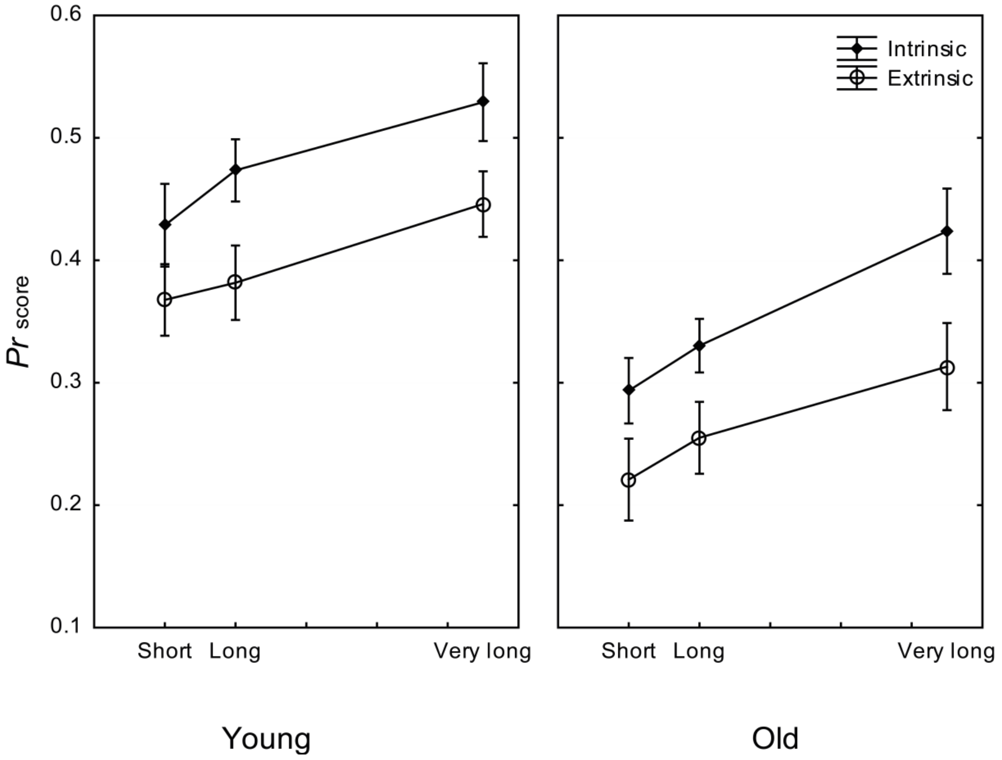

Figure 11: Corrected recognition scores (*Pr*) for trials with intrinsic and extrinsic stimuli across short, long, and very long SOAs in the main task (aggregated across change types). Performance is depicted for each age group. Processing of intrinsic and extrinsic information was not differentially affected by SOA. Error bars show 95% confidence intervals of means based on ipsative residuals (following Cousineau, 2005).

The significant interaction of SOA and change type for bound and separate single feature memory suggested that binding performance was on the level of the slowest-to-encode feature (shape) for short and long encoding intervals. However, other than bound information, single-feature memory of shape and color information seemed to profit from even extended exposure durations (see *Figure 12*). To test this, we calculated a 3 × 2 repeated-measures ANOVA, with factors SOA (short, long, very long), and change type (new color, new shape). The analysis yielded main effects of SOA, $F(2, 160) = 45.50$, $p < .001$, $\eta_p^2 = .36$, and change type, $F(1, 80) = 112.76$, $p < .001$, $\eta_p^2 = .59$, but no significant interaction, $F < 1$. This suggests, that memory performance for single features was not differentially affected by SOA, and most likely not the source of the interaction.

To investigate this, we calculated a 3 × 2 repeated-measures ANOVA, with factors SOA (short, long, very long), and change type (new shape, recombined). The analysis yielded main effects of SOA, $F(2, 160) = 19.65$, $p < .001$, $\eta_p^2 = .20$, change type, $F(1, 80) = 10.29$, $p = .002$, $\eta_p^2 = .11$, and a significant interaction, $F(2, 160) = 9.75$, $p < .001$, $\eta_p^2 = .11$. Pairwise comparisons indicated that performance for shape and binding memory did not differ at short (shape: $M = .29$, 95% CI [.25, .32], $SE = .02$; recombined: $M = .29$, 95% CI [.25, .32], $SE = .02$) and long SOAs (shape: $M = .29$, 95% CI [.25, .32], $SE = .02$; recombined: $M = .29$, 95% CI [.25, .32], $SE = .02$), with smallest $p_{\text{Bonferroni}} = .848$. However, there was a significant difference for very long SOA (shape: $M = .41$, 95% CI [.36, .45], $SE = .02$; recombined: $M = .33$, 95% CI [.29, .37], $SE = .02$), $p_{\text{Bonferroni}} < .001$. The analyses indicated that recognition performance for single features (shape, color) was similarly affected by SOA. Recognition performance for bound information reached a plateau at long encoding times and did not further increase with very long SOA. Participants were thus able to remember further single features, whereas no additional bindings were safely stored.

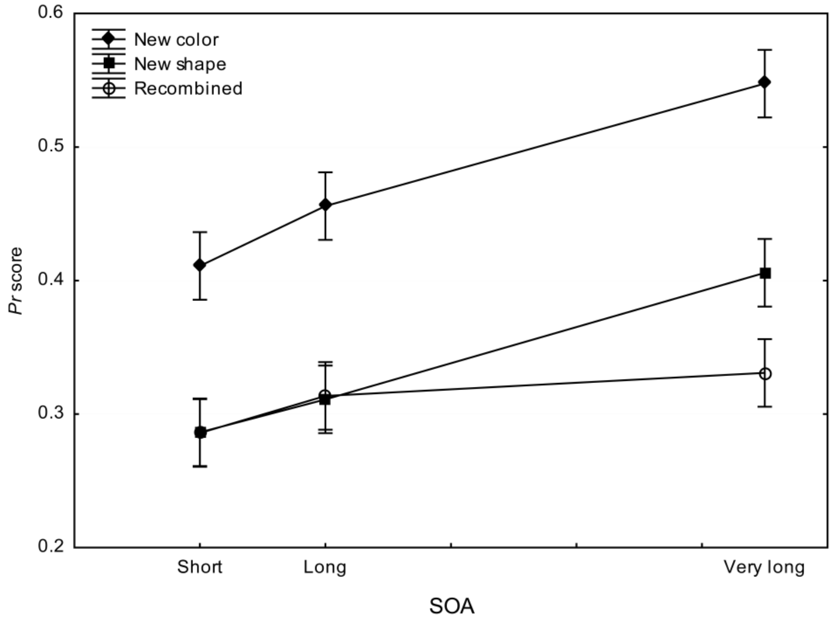

Figure 12: Corrected recognition scores (*Pr*) for trials across short, long, and very long SOAs in the main task (aggregated across stimulus types). Performance is depicted for each change type (color, shape, recombined [i.e. binding]). Whiskers show 95% within-CIs for the means corrected according to Jarmasz and Hollands (2009).

To better understand the significant three-way interaction, we analyzed the data of the two age groups in separate 2 × 3 repeated-measures ANOVAs with factors stimulus type and change type (see *Figure 13*). Data of the younger adults yielded significant main effects of stimulus type, $F(1, 40) = 49.34$, $p < .001$, $\eta_p^2 = .55$, and change type, $F(2, 80) = 116.28$, $p < .001$, $\eta_p^2 = .74$, with no significant interaction, $F < 1$. The corresponding analysis with data from older adults yielded significant main effects of stimulus type, $F(1, 39) = 47.96$, $p < .001$, $\eta_p^2 = .55$, and change type, $F(1.41, 55.13) = 33.03$, $p < .001$, $\eta_p^2 = .46$, and a significant interaction of stimulus type and change type, $F(1.72, 67.02) = 8.97$, $p = .001$, $\eta_p^2 = .19$. Pairwise comparisons indicated that younger adults performed significantly better during color change trials (intrinsic: $M = .59$, 95% CI [.54, .65], $SE = .03$; extrinsic: $M = .52$, 95% CI [.46, .57], $SE = .03$) compared to shape (intrinsic: $M = .43$, 95% CI [.37, .49], $SE = .03$; extrinsic: $M = .34$, 95% CI [.29, .39], $SE = .02$) and recombination changes (intrinsic: $M = .41$, 95% CI [.35, .46], $SE = .03$; extrinsic: $M = .34$, 95% CI [.29, .38], $SE = .02$); this pattern was observed for both intrinsic and extrinsic stimuli, with all $p_{\text{Bonferroni}} < .001$, while performance for shape and recombination changes did not differ, with smallest $p_{\text{Bonferroni}} = .146$. Results of older adults was similar to younger adults for intrinsic stimuli, with performance for color changes, $M = .46$, 95% CI [.42, .50], $SE = .02$, being superior to both shape, $M = .30$, 95% CI [.26, .35], $SE = .02$, and recombination changes, $M = .29$, 95% CI [.26, .32], $SE = .02$, with all $p_{\text{Bonferroni}} < .001$. The latter two did not differ significantly differ, $p_{\text{Bonferroni}} = .980$. A different pattern was observed for extrinsic stimuli: older adults' memory performance was not significantly different for extrinsic color, $M = .32$, 95% CI [.27, .36], $SE = .02$, and shape changes, $M = .26$, 95% CI [.22, .30], $SE = .02$, $p_{\text{Bonferroni}} = .153$. However, memory performance in the binding change condition, $M = .21$, 95% CI [.17, .25], $SE = .02$, was significantly worse than performance for shape and color change trials, with the largest $p_{\text{Bonferroni}} = .009$.

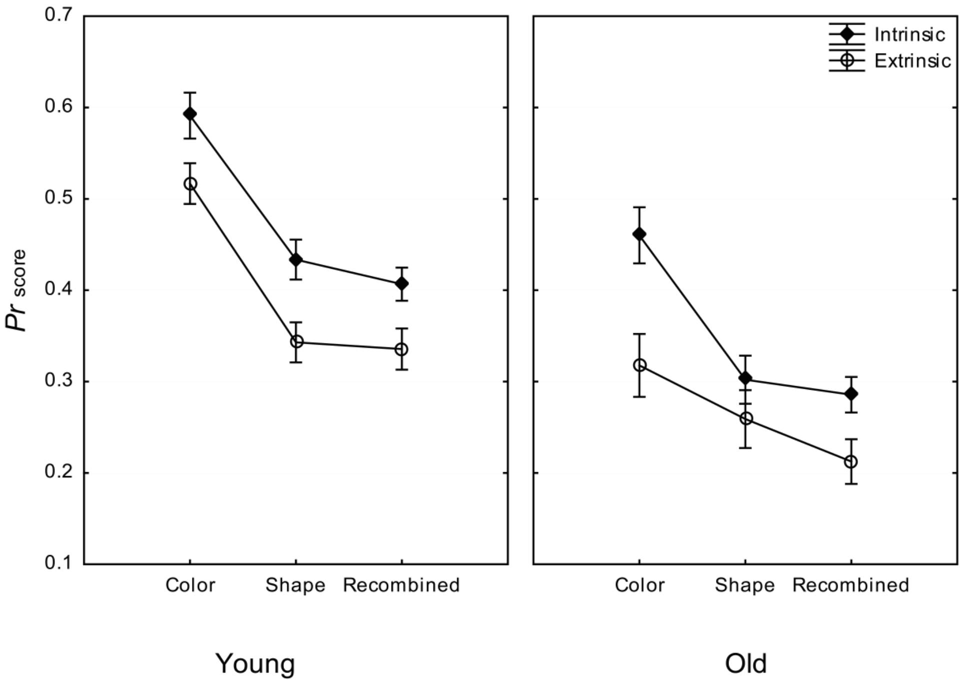

Figure 13: Corrected recognition scores (*Pr*) for trials with intrinsic and extrinsic stimuli across trials with new color, new shape or recombination changes in the main task. Performance is depicted for each age group. Error bars show 95% confidence intervals of means based on ipsative residuals (following Cousineau, 2005).

To investigate the influence of binding performance beyond mere storage of independent features, we calculated the multiplicative combination of the single-feature probabilities of new-color and new-shape changes for intrinsic and extrinsic stimuli and compared these values with the observed values in the binding conditions (see Chapter 2.3.1 for a comparable analysis). A 2 × 2 × 2 mixed-measures ANOVA with the within-subjects factors stimulus type (intrinsic, extrinsic), and value (observed, expected) and the between-subjects factor age group (young, old) yielded the already known main effects of age and stimulus type; in addition, we found that observed values, *M* = .31, 95% CI [.28, .34], *SE* = .014, were higher than the expected values predicted from the independence assumption, *M* = .18, 95% CI [.15, .20], *SE* = .012, with *F*(1, 79) = 318.67, *p* < .001, η_p^2 = .80. All interactions were nonsignificant: with stimulus type × age group, *F* < 1, stimulus type × value, *F* < 1, and the three-way interaction of all factors, *F* < 1. This indicates that the age-related deficit in the recombination condition was most likely not the result of a binding deficit, as a) binding performance was for all conditions and across age-groups higher than expected from the independence assumption, and b) the difference between observed and expected values was similar for all conditions. Thus, older adults did not perform particularly worse for extrinsic bound information; they showed decreased performance for extrinsic color information in general.

Overall, processing of extrinsic information yielded lower WM performance than processing of intrinsic information. Both age groups profited from longer exposure durations, and—as inspection of raw proportion correct scores suggested—this was likely the result of a decrease in the false alarms rate (indicating that a change happened although no change happened from study to test) as the time to encode information increased. Most important, SOA did not differentially influence information processing of intrinsic and extrinsic information for younger and older adults, neither for item nor binding memory. Age-related differences were found independent from SOA: For younger adults recognition performance was limited by the slowest-to-encode feature (shape) and rather not binding performance, irrespective of the stimulus type. For older adults, the same pattern was found for intrinsic stimuli. With extrinsic stimuli, however, older adults were less likely to process the color feature, resulting in reduced color recognition. Thus, instead of an age-related impairment in binding performance, a reduced processing of extrinsic information in general could have caused the age-related extrinsic binding deficit (see *Figure 13*).

3.5 DISCUSSION

The goal of Experiment 2 was to investigate whether intrinsic and extrinsic feature bindings are differentially affected by the time available to process the visual information. If extrinsic binding is a supplementary process, it was expected that binding impairments for extrinsic stimuli could become apparent under increased encoding demands (i.e., reduced time available to encode the information) while intrinsic binding is still intact. Moreover, this processing difference was expected to be more pronounced for older adults, if processing time is limited. Processing of bound information was assessed using shape-color associations in a masked change detection paradigm. Contrary to our expectations, varying the time available to encode the memoranda did not differentially affect older and younger adults' extrinsic and intrinsic memory performance. This was found for single feature as well as bound memory performance. Independent from encoding time, binding performance for extrinsic information was not differentially affected by age. Instead, older adults showed a more general impairment in processing extrinsic feature information. Thus, the reduced memory performance for extrinsic stimuli in WM is most likely not based a mechanism that demands for an increased time to transfer extrinsic bound information into a WM representation.

3.5.1 TRANSFERRING EXTRINSIC AND INTRINSIC INFORMATION INTO WM

The results of the present study are in line with the assumption that WM performance is influenced by the visual pattern of how the information is distributed across the object (Fougnie et al., 2010). Again, WM performance was overall better for intrinsic than extrinsic feature information, replicating previous findings (e.g., Delvenne & Bruyer, 2004; van Geldorp et al., 2015; Walker & Cuthbert, 1998). Similar to findings from Experiment 1, the processing advantage for intrinsic stimuli was found for binding as well as item memory. The present study corroborates the observation that this effect is not the result of increased visual crowding for extrinsic information (e.g., Whitney & Levi, 2011), as intrinsic and extrinsic stimuli were structurally identical. Rather, the processing benefit of intrinsic stimuli seems to be linked to an object benefit. Based on the stimuli used in the present experiment, the object benefit appears to be strong for connected features (intrinsic color and shape), while processing of features in spatial proximity (extrinsic color and shape) was more demanding. Xu (2006) argued, that the object benefit is driven by both, connectedness and proximity of features. As extrinsic stimuli were defined by proximity and intrinsic by connectedness, the present study contributes that the effect of connectedness might be more influential for the object advantage. It is, however, important to note that the present experiment did not incorporate conditions where features were completely separated across the screen; in this respect, additional research contributing to the definition of both connectedness and proximity is needed.

The processing advantage for intrinsic stimuli was constant across all SOAs as soon as perceptual encoding was sufficient. Hence, our findings indicate that the time available to process and transfer the memoranda does not differentiate extrinsic and intrinsic stimuli: Merely increasing the time is not sufficient to compensate for extrinsic WM processing demands, although this does not explicitly exclude the possibility that extrinsic binding is a supplementary binding process. Similarly, Karlsen et al. (2010) investigated the reliance of intrinsic and extrinsic feature binding on cognitive resources. The authors found no clear indications that extrinsic binding was more resource consuming than intrinsic binding. However, Karlsen and colleagues argued, that extrinsic compared to intrinsic binding might "*not emerge automatically through perceptual processes in the same manner as [intrinsic] binding*" (Karlsen et al., 2010, p. 301). The extrinsic binding process might be engaged as an additional process consuming WM resources; we, however, found no indications that this process can be understood as a time consuming cascade in the time window observed in the present experiment.

In contrast to the previous experiment, memory performance for bound information ("recombined" change type) was on the same level as memory performance for the slowest-to-encode feature (i.e., shape) for short and long encoding times. This suggests that—if only short time is available to process the information—consolidation of object features is not completely independent (Woodman & Vogel, 2008).

Moreover, whereas color and shape feature memory performance increased as SOA increased, memory performance for bound information reached a plateau after long encoding times. If we assume independent feature stores, the observed binding performance was, nevertheless, significantly better than expected from the multiplicative combination of single feature probabilities (on average $\Delta = .13$). Most important, this effect was similar for intrinsic and extrinsic stimuli and was not influenced by age.

In sum, the results indicate that individual feature information profits from increasing exposure durations, while binding performance reaches an earlier plateau. However, intrinsic and extrinsic information processing does not differentially develop along encoding demands, indicating that the processing advantage of intrinsic information is not based on a time consuming extrinsic binding cascade. At this point, it is unclear what limits binding performance.

3.5.2 AGING AND EXTRINSIC AND INTRINSIC STIMULUS PROCESSING

Findings from the comparison between younger and older adults obtained in the present Experiment 2 put weight on the assumption, that the processing advantage of intrinsic information is also not based on increased *binding* demands for extrinsic stimuli. Instead, extrinsic *feature* processing appears to be more demanding in general.

3.5.2.1 Aging and Encoding of Visual Information

Similar to Experiment 1, a general decrease in WM performance was observed for older adults. Most interestingly, as soon as a minimum of sufficient perceptual processing was ensured, memory performance of older and younger participants progressed similarly as exposure duration increased. Older and younger adults profit to similar extent from increased time available to process visual information. In the present Experiment 2, this was observed for item memory and memory for bound information. This profit was mainly the result of a gradually decreasing the false alarms rate, which has also been observed in other studies (e.g., Jost et al., 2011). We found no clear indications that age-related impairments in WM are the result of reduced ability to quickly consolidate information into WM, neither for feature memory nor memory for feature associations. This outcome is in line with previous results from Rhodes and colleagues (2016) and

Brown et al. (2017), suggesting that increasing the time available to process the visual information does not improve WM performance under all conditions. The present study extends these findings with individually estimated variations of encoding time.

3.5.2.2 Aging and Processing of Intrinsic Information

Besides a more general age-related reduction in WM performance, no dedicated age-related binding deficit was observed for intrinsic stimuli. This finding replicates observations from Experiment 1 and previous studies (Brockmole et al., 2008; Brockmole & Logie, 2013; Parra et al., 2009; Peterson & Naveh-Benjamin, 2016; van Geldorp et al., 2015). Older adults' memory for recombined features, which—compared to new feature changes—requires retrieval of exact binding information, was on a similar level as memory for shape features. This lets us assume that processing intrinsic information in the given Experiment 2 did not place additional demands on WM functioning beyond processing the slowest-to-encode feature (i.e. shape; for comparable results, see Brown et al., 2017; Woodman & Vogel, 2008). Although this finding in isolation does not necessarily indicate that intrinsic binding is automatic or obligatory, the present experiment found that the effect was independent of the time available to encode the information. Moreover, the observation was found for younger and older adults. The lack of influence of exposure duration indicates that the transfer of intrinsic bindings seems to take place without observable costs beyond the processing of the most complex feature (Zimmer & Ecker, 2010).

3.5.2.3 Aging and Processing of Extrinsic Information

Experiment 2 yielded a significant age-related binding deficit for extrinsic stimuli, as frequently assessed by a significant interaction of age group and binding type for single and bound information. However, Rhodes et al. (2017) discussed that the evidence of interaction does not necessarily prove the existence of an age-related binding deficit. We, therefore, contrasted memory performance for observed and expected binding performance and found that memory performance for extrinsic bound information was not disproportionally affected in older adults. Instead, findings indicated that the reduced performance in the binding condition is most likely the result of older adults reduced ability to process extrinsic color feature information in general, since memory for bound information is only feasible if all single features are available. This observation was independent of exposure duration.

Binding performance for older and younger adults was even higher than expected if independent features would be stored. This suggests that some information about feature bindings was represented. However, we have no indications that there is any additional binding mechanism beyond the intentional joint encoding of features increasing the likelihood that corresponding features are represented together.

It is debatable what caused this decrease in older adults WM performance in processing extrinsic features. Contrary to our expectations, the present results do not support the assumption that the engagement of an extrinsic binding process is more time-consuming in older adults. Rather, older adults might be less able to modulate their attentional focus between intrinsic and extrinsic feature distributions. While color is an inherent part of the shape information during intrinsic trials, extrinsic stimuli demanded an adaption of the attentional focus from the shape to the surrounding frame. Older adults might experience increasing difficulties in executing the adequate scope of attention (e.g., Greenwood & Parasuraman, 1999, 2004). It is further discussed that information processing is associated with increasing "noise" as age progresses. The noise requires increasing top-down interventions to compensate for and solve the task (Cabeza, 2002; Reuter-Lorenz & Cappell, 2008). Older adults' reduced ability to process extrinsic feature information might be based on extrinsic information giving less "room" for compensation processes if the time to process the information falls under a certain threshold.

3.5.3 CONCLUSIONS AND CAVEATS

Experiment 2 yielded the following results: (a) The distinction between intrinsic and extrinsic items influences visual WM performance. This replicates findings from Experiment 1, indicating that memory performance for extrinsic information is overall lower than memory performance for intrinsic information. This was the case for single-feature as well as binding memory. (b) The time available to transfer the visual information into a stable representation does not influence intrinsic and extrinsic information processing differently, neither with younger nor older participant groups. (c) Binding processes in early phases of WM consolidation are not distinguishable from single feature processing. (d) Besides a general age-related memory deficit, older adults exhibited a selective processing deficit for extrinsic features information that was independent from exposure duration. In sum, these results suggests, that the binding mechanisms is not a key determinant for the processing difference between intrinsic and extrinsic stimuli. Observed processing differences between both stimulus types could rather be the result of extrinsic stimuli posing increased demands on modulate the scope of attention between parts of a stimulus.

Experiment 2 yielded no indications that the age-related binding deficit is a result of impaired late processes when the fleeting perceptual representation is transferred in a stable WM representation. Processing intrinsic and extrinsic information showed no clear dependence on the time available to transfer the information from a percept into a WM representation, neither for single nor bound features. Instead, the overall reduced recognition performance for extrinsic bound and extrinsic color features indicates that age-related changes to WM performance are the result of changes to earlier selection mechanisms. This interpretation is in line with the results from the indirect test in Experiment 1: if not equipped with sufficient time to initiate cognitive control processes to intentionally process the information, or, if the information itself is not intentionally heeded, older adults exhibit a reduced probability to process extrinsic information.

In addition to terminating stimulus processing, the masks may also have influenced the results by interference effects in the maintenance phase. Such suffix effects were reported by Brown and colleagues (Experiment 3; 2017). In their experiment, older and younger adults studied intrinsic colored shapes in a change detection task. During the maintenance interval, the authors presented an additional but task-irrelevant item 250 ms after the study array disappeared. The to-be-ignored information disrupted older adults WM performance for bound information to a greater extent than WM of younger adults. Brown and colleagues argued that older adults binding deficits could be the result in a reduced ability to protect WM representations from interference. Similarly, van Geldorp et al. (2015) found older adults WM performance to be more affected by secondary task that had to be solved in parallel to a change detection paradigm. Moreover, Jost et al. (2011) reported, that older adults show delayed filtering abilities compared to younger adults. These findings suggest that memory performance could also be influenced the mask stimuli and memory performance for intrinsic and extrinsic features and associations could therefore be underestimated. As the present paradigm was not suited to contrast the time given to process the information with suffix-free conditions, further research is needed to disentangle these potential factors. One way to assess the maintenance demands of information, without relying on dual-task or suffix effects, is to measure the electrophysiological signal associated to storage demands (e.g., the CDA; see Chapter 1.2.2.1). Such an investigation is the subject of Experiment 3.

All results are confined to the rather broad time range investigated in this Experiment 2. However, we cannot make a clear statement about the rate at which different features are consolidated. In order to be able to make a more precise statement on this, equidistant smaller subdivisions of earlier processing phases are required (e.g., Sun et al., 2011; Woodman & Vogel, 2008). Moreover, consolidating information into WM might not follow a linear trend; instead, some time ranges might be of greater importance for WM than others, making future research necessary.

4 EXPERIMENT 3: INTRINSIC AND EXTRINSIC FEATURE REPRESENTATIONS DO NOT DIVERGE DURING MAINTENANCE

Experiment 1 and 2 corroborated existing findings that intrinsic and extrinsic stimuli pose different demands on the WM system (Allen, 2015). Processing extrinsic feature information appears to be more susceptible to age-related degradation than intrinsic information. However, the data suggest that this is most likely not the results of a more (time-)demanding extrinsic binding process (Experiment 2) during encoding. Instead, increased attentional control appears to be needed to process extrinsic information in general (Experiment 1 and 2).

However, previous behavioral findings suggest that the cognitive demands to *maintain* intrinsic and extrinsic stimuli in WM could differ significantly: For example, van Geldorp et al. (2015) found that an additional cognitive task during the maintenance phase differently affects the representation of intrinsic an extrinsic stimuli. When participants were required to count backward in parallel to solving a change detection task, the authors found that participants were less well able to retrieve extrinsic object feature bindings compared to intrinsic. Peterson and Naveh-Benjamin (2016) found that older adults exhibit an age-related deficit in maintaining extrinsic object-context bindings. However, this deficit disappeared when articulatory suppression was administered in younger adults: the authors argued that the expression of a binding deficit was influenced by the availability of verbal rehearsal strategies. In addition, while Karlsen et al. (2010) reported that the withdrawal of cognitive resources during the maintenance phase via a concurring secondary task (backward counting) did not differentially affect the retention of intrinsic and extrinsic shape-color associations. In sum, behavioral findings on the maintenance demands of both stimulus types are far from being conclusive.

Experiment 3 is set out to investigate the maintenance demands of intrinsic and extrinsic stimuli via electrophysiological correlates while changing the task-relevance of features. If extrinsic stimuli pose increased demands on the maintenance process, electrophysiological signal should vary accordingly. Moreover, as intrinsic but not extrinsic object-features should be represented unintentionally, varying the task-relevance of features should provoke differences in the electrophysiological maintenance signal of extrinsic but not intrinsic stimuli.

As introduced in Chapter 1.2.2.1, one electrophysiological signal that is argued to track the amount of information maintained in WM is the CDA (see Luria et al., 2016, for an overview). This difference wave is based on the hemispheric organization of the visual system: information presented to the left visual hemifield is processed in the contralateral brain hemisphere, and vice versa. By subtracting the neural activity recorded ipsilateral to the target, neural activity unrelated to the processing of the task-relevant visual information is reduced. The amplitude of the CDA is shown to be sensitive to the amount of information stored in WM; the more units an observer stores in WM, the more pronounced the CDA is during the retention interval (e.g., Quak et al., 2018; Vogel et al., 2005; Vogel & Machizawa, 2004). The CDA is, hence, discussed to indicate the number of units currently represented in WM.

Moreover, the CDA is also found to be related to maintenance demands depending on object characteristics: The CDA is found to be more negative for objects with increased informational load. For example, Luria et al. (2010) found that the CDA is enhanced if the complexity of the memoranda is increased. The authors compared WM performance for simple color patches and complex polygons in a change detection task, while they recorded the electrophysiological signal. Given similar set sizes, the authors found the amplitude of the CDA for polygons to be more negative than for colors. A similar relationship between the visual demands of the memoranda and the amplitude of the CDA was also observed by Luria and Vogel (2011; see also Gao et al., 2009). Gao et al. (2013) found that the CDA increases from two to four memoranda as long as simple stimuli were presented. No such increased was observed if complex objects were presented. The CDA, thus, not only reflects the pure number of objects in WM but is to a certain extent also influenced by the visual demands of the memoranda. Provided that WM capacity is not exhausted, the CDA appears to be a useful tool to examine the maintenance demands different stimulus types.

The maintenance of intrinsic and extrinsic representations could pose different demands on the WM system. To reiterate, according to the type-token model (Zimmer et al., 2006; Zimmer & Ecker, 2010), intrinsic features are associated within an object token, a residuum of an object files generated during perception. In contrast, extrinsic binding associates at least two (perceptual) units (e.g., an object in its context) into episodic tokens, representing higher-order representations that integrate objects tokens and their context. If we transfer these assumptions to WM, there are at least two possible ways, how information is maintained: first, if extrinsic information can be integrated in some form of "*higher level*" (Ecker et al., 2013, p. 226) representation, intrinsic and extrinsic objects are both represented as a single entity. However, if extrinsic object information is not maintained as an integrated representation but as associated entities, the corresponding disjunct feature information has to be maintained in separate representations.

With respect to the framework of the type-token model (Zimmer & Ecker, 2010), specific hypotheses arise for the CDA to behave during a change detection task with intrinsic and extrinsic stimuli. (1) On behalf of the assumption that intrinsic and extrinsic stimuli represent different types of representations: If extrinsic stimuli are represented as disjunct visual units in WM, we would expect the CDA to be more pronounced for intentionally stored extrinsic shape-color associations than for intrinsic associations. If extrinsic features are maintained as an integrated higher-level representation in WM, intrinsic and extrinsic stimuli should produce comparable CDA waveforms, as one unit is represented in either case. (2) On behalf of the assumption that the processing of extrinsic but not intrinsic feature information differs depending on task demands: If participants are instructed to only remember the shape information of a colored stimulus, a) similar CDA amplitudes are expected for intrinsic stimuli irrespective of color being task-relevant or irrelevant; color should be unintentionally integrated into the WM representation under both conditions; b) if the retention of extrinsic information is more demanding, the CDA is expected to be more pronounced for trials were color is a task-relevant feature compared to trials where color is a task-irrelevant feature, as extrinsic information is not expected to be involuntarily processed.

To test these hypotheses, younger participants completed a bilateral version of a change detection task, while the electrophysiological signal was recorded. Participants studied sets of colored shapes (intrinsic stimuli) or white shapes encased in colored frames (extrinsic stimuli). Comparable sets of stimuli were presented bilateral to a central fixation cross and participants were required to only store the stimuli from one hemifield. Participants completed the task under two conditions: Comparable to Experiment 1, intentional and unintentional processing of object-feature associations was assessed by varying the task-relevance of the object features. In the shape and color test, participants were instructed to memorize the shape-color associations; in the shape test, participants memorized only the shapes. A single test probe was either identical to a study item (no change), or it contained an unstudied shape or color (new shape/new color change). The probe was presented in a hemifield-central position to minimize influences of object-location binding and increase the demands of retaining correct shape-color associations (Cowan et al., 2013; van Geldorp et al., 2015).

4.1 METHODS

The experiment used repeated-measures design with factors test type (shape test/shape and color test), stimulus type (monochrome/intrinsic/extrinsic), and change type (no change/new shape/new color). In the shape test, only shape information of the memoranda was task-relevant; in the shape and color test, both shape and color of an object were task-relevant.

4.1.1 PARTICIPANTS

In total, 31 right-handed undergraduate students of Saarland University participated in the study. Data of two participants was excluded from analyses due to excessive errors; data of two additional participants was excluded due to excessive artifacts in the ERP signal. The final sample consisted of 27 participants (22 women, 5 men), ranging from age 19 to 30 years (M = 23.56 years, SD = 2.69).

All participants reported normal or corrected-to-normal vision, no clinical diagnose of migraine or epilepsy, no history of neurological disorders (within the last 5 years), and no current intake of pharmaceutical preparations that could influence RTs. After the nature of the study was explained, participants signed written informed consent after reading an ethically approved information sheet. All participants received a monetary compensation of €8 per hour. The study was performed according to the approval of the Ethics Committee of the Philosophical Faculty III Empirical Human Sciences at Saarland University.

Participants' mean score in the digit symbol substitution test as an estimator of processing speed adapted from Wechsler (2008) was M = 70.89 (SD = 8.46). The mean score in the multiple-choice knowledge test as an estimator for crystallized intelligence (adapted from Lehrl, 1977) was M = 30.42 (SD = 2.62). Scorings were comparable to younger samples from the previous Experiments 1 and 2.

4.1.2 MATERIALS AND APPARATUS

The same set of nine simple geometric shapes as in Experiment 2 was used. Each shape was encased with a spatially separated quadratic frame. In the intrinsic condition, the shape was colored with one of seven different colors and the frame was always white (RGB values in parentheses; 255, 255, 255). In the extrinsic condition, the shape was always white and the frame was colored with one of the seven different colors. The colors used were blue (49, 78, 144), cyan (109, 198, 217), green (58, 170, 53), yellow (243, 230, 0), red (229, 36, 32), purple (166, 82, 154), and brown (153, 102, 51). All stimuli were presented on a gray (128, 128, 128) background. Shape-stimuli subtended 1.00° × 1.00° of visual angle, the surrounding frame 1.49° × 1.49° of visual angle. The width of the frame was 0.28° of visual angle, thus creating a spatial separation between the shape and the frame. The experiment was presented on a 23-inch flat screen with a resolution of 1,920 × 1,080 pixel at a refresh rate of 60 Hz. Participants were seated in front of the screen at an approximate viewing distance of 60 cm.

4.1.3 PROCEDURE

Participants solved a bilateral version of a change-detection task. The trial structure is illustrated in *Figure 14*. Each Trial began with a fixation cross presented in the center of the screen. Participants were instructed to remain their gaze on to the fixation cross. After 200 ms, the fixation cross changed into a cue word, specifying the upcoming task: Similar to Experiment 1, the cue “BEIDES” (both) indicated the shape and color test, where participants were required to store the shape-color associations of the presented stimuli. The cue “FORM” (shape) indicated the shape test, where participants were required to retain only the shape of the presented stimuli, with color being irrelevant to the task. The cue word lasted for 800 ms and was replaced by a fixation cross for 600 ms to ensure sufficient time for task-preparation. Compared to Experiments 1 and 2, the cue interval was extended to take account for the more complex trial structure. Afterward, two arrows were faded in below and above the fixation cross for 200 ms, indicating the to-be-attended hemifield for the given trial. Following a jittered delay of 300 to 400 ms with only the fixation cross in the center of the screen, the bilateral memory array was presented for 200 ms: Two stimuli appeared at each hemifield. The reduced set size compared to previous experiments was chosen to avoid artificially limiting the range of variation of the CDA (see Luria & Vogel, 2011). The stimuli were pseudo-randomly distributed on an imaginary circle of 7° of visual angle in diameter around the center of the screen. At each hemifield, both stimuli were presented with a minimal distance of 4.28° of visual angle from center to center. Each stimulus consisted of a different color and shape, with no repetition allowed within the memory array. After a retention interval of 1000 ms, when only the fixation cross was displayed as a visual aid for the participant to remain their gaze on the center of the screen, the bilateral test array appeared. A single probe stimulus was presented in either hemifield, and each probe was located in the middle between the locations previously occupied by the studied stimuli. Spatial information was not relevant to the task. During shape and color test conditions participants indicated whether the presented shape-color combination in the attended hemifield was same or different to one of the two studied stimuli. During shape test conditions, participants indicated whether the presented shape in the relevant hemifield was same or different to one of the studied shapes. When a change was realized, this was done only in the relevant hemifield, while the not-to-attend hemifield displayed a no-change condition. Participants responded via button press on a Cedrus response pad (RB-834, Cedrus Corporation, San Pedro, California, USA). Response categories (match/non-match) were assigned to the response buttons in counterbalanced order across subjects. The probe stimulus was presented until a response was captured or for a maximum of 2,000 ms. If participants exceeded the time available to respond, they were informed via the cue “Zu langsam” (too slow) flashing for 400 ms after test display disappeared. The trial ended with an inter-trial interval of 600 ms, displaying only the fixation cross. Both accuracy and response speed were emphasized.

Participants completed a total of 600 trials, realizing 24 conditions. In half the trials (300), participants attended the right hemifield, in the other half the left hemifield. Across both hemifields, 240 trials presented extrinsic stimuli, 240 trials intrinsic stimuli, and 120 trials monochrome stimuli. Monochrome stimuli served as a control condition that displayed only shape but no color information. 60 of the monochrome trials were (shape) change trials, and 60 were no change trials. For intrinsic and extrinsic stimuli each, half the trials (120) belonged to shape and color test condition and half to the shape test condition. In each test condition, half the trials (60) were change trials and half required a no-change response. Thus, in the shape and color test condition, shape change occurred in 30 trials and color changes in 30 trials. In the shape test condition, 60 trials were devoted to the shape change condition, with no color change happening in the shape test. Trials were in random order. Every 40 trials, participants could take a self-paced break. Each participant performed 72 practice trials that were not included into data analyses. With the preparation for EEG recording, Experiment 3 lasted approximately 2 to 2.5 hours.

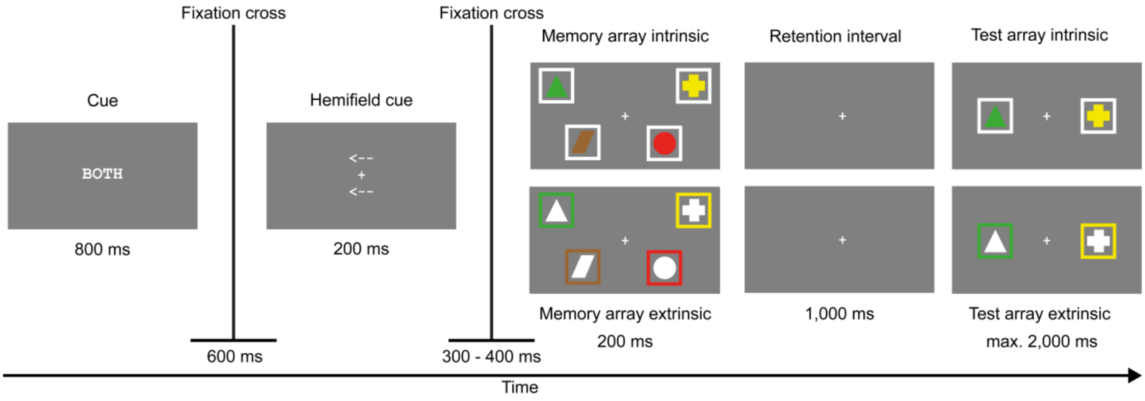

Figure 14: Schematic illustration of the trial structure of Experiment 3, not drawn to scale. A "`SHAPE`" cue was associated with the shape test; a "`BOTH`" cue was associated with the shape and color test. In the example, for both the shape test condition and the shape and color test condition, a "no change" trial is depicted (i.e., the test probe shows a studied shape and the corresponding color; thus, neither for the shape test, nor for the shape and color test, a relevant feature was changed).

4.1.4 ELECTROPHYSIOLOGICAL RECORDINGS AND ANALYSIS

32 active Ag/AgCl electrodes (Acticap, Brain Products, Munich, Germany) mounted on an elastic cap were placed in a subset of the International 10-20 System (Fp1, Fp2, F3, F4, F7, F8, Fz, C3, C4, Cz, P3, P4, Pz, O1, O2) with additional nonstandard positions mainly placed on the posterior and parietal sites (FC1, FC2, CP1, CP2, CP5, CP6, PO7, PO8, O1, O2). The ground electrode was mounted on AFz. Electrode site signals were recorded referenced to the left mastoid and were later re-referenced offline to the linked mastoids. Horizontal electrooculogram was recorded by electrodes mounted at the outer canthi of the eyes. Vertical electrooculogram was recorded with one electrode centered below and one above the right eye. All impedances were kept below 5 kΩ. Electrode signals were amplified by a DC coupled Brain Amps amplifier (Brain Products, Munich, Germany). Signals were recorded at a sampling rate of 1,000 Hz/channel, but later down-sampled to 256 Hz for analyses.

Preprocessing and data analyses were conducted with BrainVision Analyzer (Version 2.1.1.357, Brain Vision, LLC). A high-pass filter of 0.01 Hz, 12 dB/octave, was applied to the continuous signal (see Luck, 2014). The signal was segmented into epochs beginning 200 ms prior to the memory array onset and ending 1200 ms after study display onset, thus covering the study and maintenance phase. Incorrect or missed trials were neglected. The epochs were filtered with low-pass filter of 30 Hz, 24 dB/octave, following the recommendations from Luck (2014). Epochs were baseline corrected according to the 200 ms before the onset of the memory array. Eye-movement and blink correction was done according to the method described by Gratton, Coles, and Donchin (1983); if no sufficient number of blinks was captured, epochs containing blinks were rejected. Epochs were scanned for artifacts according to the following criteria: maximal allowed voltage step between two successive sampling points: 30 µV; maximal allowed difference of values in an interval of 200 ms: 100 µV; maximum amplitude in the recording epoch, ±100 µV: lowest allowed activity within an interval of 100 ms: 0.5 µV. On average, this led to the loss of 5.06% of the epoch data.

Based on previous studies (Jost et al., 2011; Luria et al., 2016; Vogel et al., 2005; Vogel & Machizawa, 2004), analysis of the CDA was restricted to posterior and occipital electrode sites. Due to the bilateral study display but central gaze fixation, stimuli on the attended site were expected to elicit signals reflecting perceptual and WM processing most prominent on the contralateral brain hemisphere; in the ipsilateral hemisphere, only task-unspecific signals of processing should be recorded. To quantify the CDA, the difference wave was calculated by subtracting the activity on electrodes ipsilateral to the study display from the corresponding contralateral electrode. The electrophysiological activity during the time-window from 500 to 900 ms after the offset of the study display was used for statistical analyses. Visual inspection was used to determine the electrodes where the CDA was most prominent on posterior and occipital electrodes. Following precedent, ERP data analyses were thus conducted on electrode sites PO7 and PO8 (e.g., Balaban & Luria, 2015, 2016; McCollough et al., 2007; Peterson, Gozenman, Arciniega, & Berryhill, 2015).

4.2 RESULTS – BEHAVIORAL DATA ANALYSES

A trial exclusion similar to the previous Experiments 1 and 2 resulted in the exclusion of 2.70% of the behavioral trial data (Hoaglin et al., 1986; Hoaglin & Iglewicz, 1987). The dependent variables were recognition accuracy and RT. As RTs were still nonnormally distributed, analyses on RTs were based on log10-transformed data. As results did not differ qualitatively and for ease of comprehension, we report descriptives based on the untransformed RT data. Recognition accuracy was scored as corrected recognition (*Pr* scores, see Experiment 1). In the shape and color test, correctly detecting a color or shape change from study to test was coded as a “hit”, indicating that no change happened if nothing was changed was coded as a “correct rejection”. *Pr* scores were calculated as an aggregate of both change conditions, that is the mean performance across color and shape changes. In the shape test, a “hit” was defined as correctly identifying a shape change. If homogeneity of variances was violated during statistical analyses, Greenhouse-Geisser-corrected degrees of freedom are reported. Follow-up analyses using pairwise comparisons were Bonferroni-corrected if needed, as indicated by the subscript. *Table 5* shows mean accuracy and RTs across all conditions that served as the basis for the data analyses.

Table 5: Accuracies and RTs for the shape test and the shape and color test across stimuli and change types in Experiment 3

Test	**Stimulus**	**Change type**	**ACC (*SD*)**	**RT (*SD*)**
Shape	Extrinsic	No change	.87 (.09)	666 (99)
		Shape change	.90 (.08)	707 (105)
	Intrinsic	No change	.89 (.11)	656 (102)
		Shape change	.87 (.10)	699 (111)
	Monochrome	No change	.85 (.11)	676 (100)
		Shape change	.94 (.09)	684 (101)
Shape and color	Extrinsic	No change	.82 (.12)	656 (86)
		Color change	.87 (.13)	731 (108)
		Shape change	.86 (.12)	696 (106)
	Intrinsic	No change	.85 (.11)	655 (104)
		Color change	.91 (.08)	701 (106)
		Shape change	.86 (.12)	705 (104)

Note. ACC = accuracy; RT = response time in ms; SD = standard deviation; standard deviation is depicted in parentheses.

4.2.1 SHAPE TEST

A repeated-measures ANOVA on *Pr* scores in the shape test with the factor stimulus type (monochrome, intrinsic, extrinsic) yielded no significant effect of stimulus type, with recognition performance being equal for monochrome stimuli, *M* = .79, 95% CI [.72, .86], *SE* = .034, intrinsic stimuli, *M* = .76, 95% CI [.70, .82], *SE* = .029, and extrinsic stimuli, *M* = .76, 95% CI [.71, .82], *SE* = .026, *F*(2, 52) = 1.36, *p* = .27, η_p^2 = .05. Color information did not influence recognition performance if participants had to memorize shape information only.

A repeated measures ANOVA on log-transformed RTs with factors stimulus type (monochrome, intrinsic, extrinsic) and change type (no change, shape change) in the shape test yielded a main effect of change type, with RTs being slower for change trials, *M* = 697 ms, 95% CI [651, 738], *SE* = 20, than for no change trials, *M* = 666 ms, 95% CI [627, 704], *SD* = 19, with *F*(1, 26) = 6.70, *p* = .016, η_p^2 = .21. There was no significant effect of stimulus type, *F*(1.55, 40.20) = 1.41, *p* = .254, η_p^2 = .05, but a significant interaction of stimulus type and change type, *F*(2, 52) = 14.31, *p* < .001, η_p^2 = .36.

To investigate the interaction of stimulus type and change type, difference scores between change and no change trials were calculated. Pairwise comparisons indicated that the RT prolongation during change trials for monochrome stimuli, *M* = 8 ms, 95% CI [-19, 35], *SE* = 13, was significantly shorter (largest *p* = .001) than the prolongation for intrinsic, *M* = 44 ms, 95% CI [19, 69], *SE* = 12, and extrinsic stimuli, *M* = 41 ms, 95% CI [18, 65], *SE* = 12. The latter two did not differ significantly, *p* > .99. Although not task-relevant, adding a color influenced the RT during trials with a task-relevant shape change; this influence was similar for intrinsic and extrinsic color features.

4.2.2 SHAPE AND COLOR TEST

Paired t-tests on *Pr* scores in the shape and color test revealed that recognition accuracy was lower for extrinsic stimuli, M = .69, SD = .16, than for intrinsic stimuli, M = .74, SD = .14, $t(26) = 3.41$, $p = .001$, $d_{\text{Cohen}} = .66$. If feature associations were task-relevant, the stimulus type influenced recognition performance.

A repeated-measures ANOVA on log-transformed RTs with factors stimulus type (intrinsic, extrinsic) and change type (no change, feature change) in the shape and color test yielded a main effect of change type, with RTs during trials with feature changes being longer, M = 708 ms, 95% CI [669, 748], SE = 19, than during trials without feature changes, M = 654 ms, 95% CI [617, 691], SE = 18, $F(1, 26) = 25.09$, $p < .001$, $\eta_p^2 = .49$. No other effect was significant[5]. Thus, RTs for shape-color associations were influenced by change type, but were not influenced by the pattern of how features were distributed across the stimuli.

4.3 RESULTS – ERP DATA ANALYSES

CDA waveforms for the different conditions in the shape test task and the shape and color test task are presented in *Figure 15* and *Figure 16*, respectively.

4.3.1 SHAPE TEST

Mean CDA amplitude values of the shape test were entered in a repeated-measure ANOVA with factor stimulus type (monochrome, intrinsic, extrinsic). The analysis yielded no main effect of stimulus type, with $F < 1$. Mean CDA amplitudes reached a comparable value for all stimulus conditions, with monochrome: M = -0.71 µV, 95% CI [-1.03, -0.38], SE = .16; intrinsic: M = -0.55 µV, 95% CI [-0.95, -0.14], SE = .20; and extrinsic: M = -0.73 µV, 95% CI [-1.04, -0.42], SE = .15. The mean amplitude of the CDA did not vary across stimulus types if participants attended the shape information only.

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[5] Stimulus type: $F < 1$; Interaction stimulus type × change type: $F(1, 26) = 1.56$, $p = .222$, $\eta_p^2 = .06$.

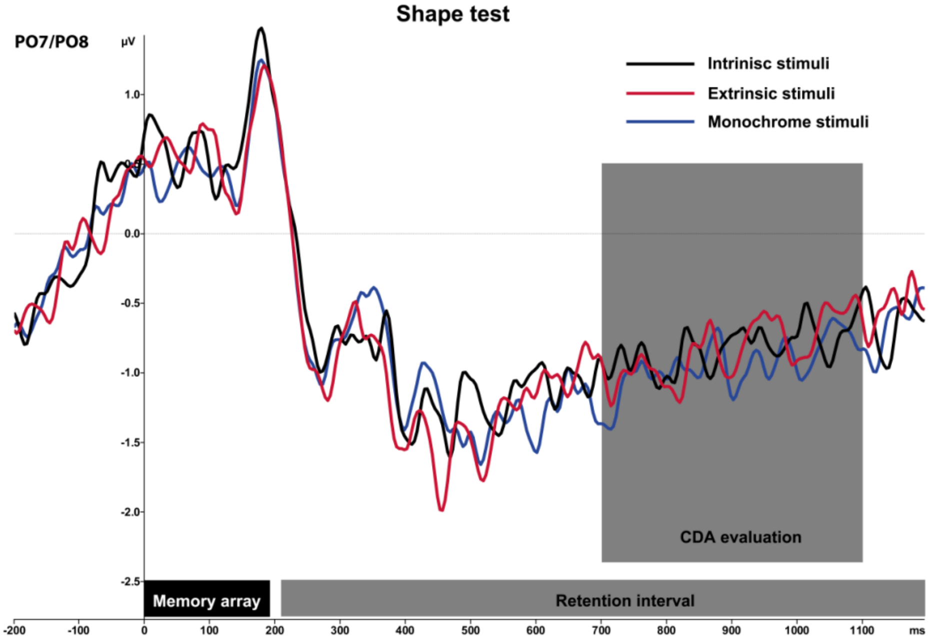

Figure 15: Grand-averaged ERPs in the shape test time-locked to the memory array. Depicted is the CDA amplitude for each stimulus type. Gray boxes highlight the time period of interest.

4.3.2 SHAPE AND COLOR TEST

In the shape and color test, a dependent sample t-test on mean CDA amplitudes revealed no significant difference between extrinsic and intrinsic stimuli, with mean amplitude for extrinsic stimuli, M = -0.54 µV, SE = .23, being not significantly different from intrinsic stimuli, M = -0.84 µV, SE =.20 , $t(26)$ = 1.33, p = .196, d_{Cohen} = .26. CDA amplitudes were not influenced by the type of stimulus if all object features were task-relevant.

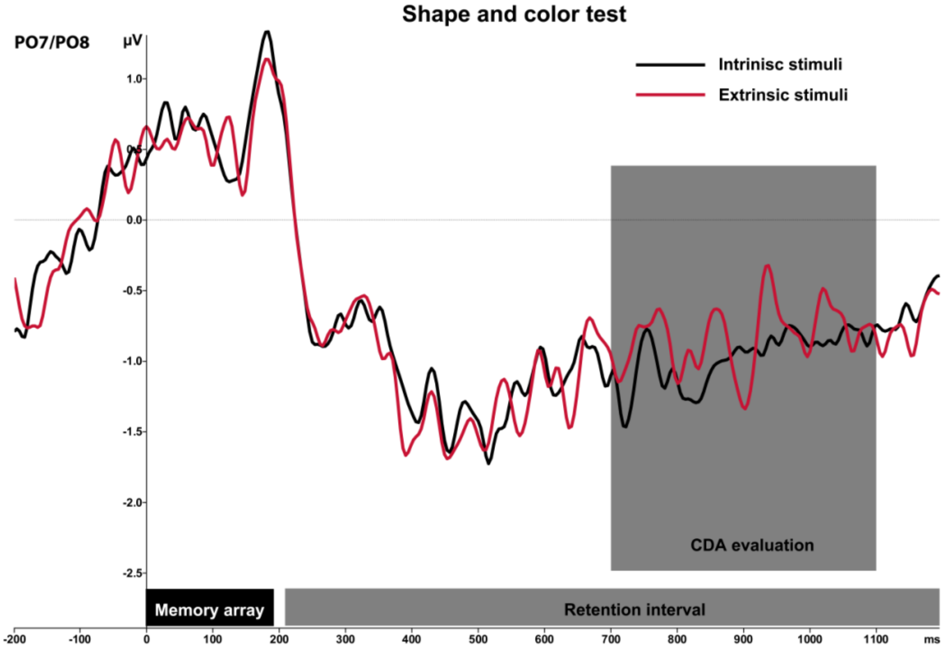

Figure 16: Grand-averaged ERPs in the shape and color test time-locked to the memory array. Depicted is the CDA amplitude for each stimulus type. Grey boxes highlight the time period of interest.

4.3.3 COMPARISON OF INTENTIONALLY AND UNINTENTIONALLY STORED FEATURES

A paired sample t-test for intrinsic stimuli revealed that mean CDA amplitude with only relevant shape features, M = -.55 µV, SE = .20, was not significantly different from mean CDA amplitude for intrinsic stimuli with both relevant shape and color features, M = -.84 µV, SE = .20, with $t(26) = 1.54$, $p = .137$, $d_{\text{Cohen}} = .30$. Similarly, paired sample t-tests for extrinsic stimuli indicated that mean CDA amplitude with only relevant shape features, M = -.73 µV, SE = .15, was not significantly different from the mean CDA amplitude for extrinsic stimuli with both relevant shape and color features, M = -.54 µV, SE = .23, with $t(26) = 1.03$, $p = .157$, $d_{\text{Cohen}} = -.20$. The amplitude of the CDA was not influenced by the number of relevant object features, neither for intrinsic nor extrinsic stimuli.

4.3.4 COMPARISON TO THE CONTROL CONDITION

As indexed by paired sample t-tests, monochrome stimuli with no additional color feature elicited a mean CDA amplitude, M = -.71 µV, SE = .16, that was neither significantly smaller than the mean amplitude elicited by intentionally stored intrinsic shape color associations, M = -.84 µV, SE = .20, $t(26) = 0.64$, $p = .737$, $d_{\text{Cohen}} = .12$, nor intentionally stored extrinsic shape color associations, M = -.54 µV, SE = .23, $t(26) = -0.87$, $p = .196$, $d_{\text{Cohen}} = -.17$. The observed CDA did not vary with the number of object features.

4.4 DISCUSSION

Findings from LTM studies suggest that the representations of intrinsic and extrinsic feature associations can differ. While intrinsic representations are considered single object tokens, extrinsically associated information represents higher-order representations in which two or more tokens are integrated (e.g., Zimmer & Ecker, 2010). The present Experiment 3 is sought to investigate the cognitive demands related to maintaining intrinsic and extrinsic stimuli in visual WM. Previous studies indicated that the CDA is influenced by the informational load of the memoranda (e.g., Luria et al., 2010) and the visual pattern with which the task-relevant information is presented (e.g., Luria & Vogel, 2011). We expected the CDA to vary with the stimulus type of the to-be-remembered information. In contrast to the behavioral effects observed at test, intrinsic and extrinsic stimuli do not pose different demands on the maintenance phase as indicated by the CDA (for an overview on mean CDA amplitudes during the maintenance phase, see *Figure 17*). The results provide first indications that disjunctive extrinsic object features can be maintained as an integrated object representation.

4.4.1 BEHAVIORAL FINDINGS FOR INTRINSIC AND EXTRINSIC FEATURE ASSOCIATIONS

On a behavioral level, recognition performance was not differentially influenced by the addition of task-irrelevant intrinsic or extrinsic color features. However, adding a color feature prolonged the time necessary to evaluate the test probe on a general level. This replicates findings suggesting that the visual WM is influenced by the number of features and does not operate in an all-or-non manner (e.g., Oberauer & Eichenberger, 2013). If participants intentionally stored the shape-color associations, recognition performance was significantly lower for extrinsic compared to intrinsic stimuli. The behavioral findings support the assumption that extrinsic feature combinations place higher demands during a change detection task than intrinsic associations. This replicates findings from previous studies (e.g., Ecker et al., 2013; Wilson et al., 2012) and extends these observations to other paradigms, such as the hemifield paradigm.

Moreover, the behavioral findings indicate, that the visual WM is not solely limited by a finite number of objects, as it would be expected if the nature of the representation is the whole object (e.g., Luck & Vogel, 1997). Instead, an increase in informational load by adding a (task-irrelevant) color feature influenced WM performance in terms of RT or recognition performance (for similar results, see, e.g., Gao et al., 2009; Luria et al., 2010; Luria & Vogel, 2011).

From the observed behavioral data, however, no strong conclusions can be drawn on what drives the differences between intrinsic and extrinsic information: The data suggests that more features pose higher demands on some form of finite mental resource available to process the information. These costs appear to be larger for extrinsic compared to intrinsic feature combinations. These findings are in line with models assuming that to-be-remembered information consumes from a flexible resource available for WM processing (e.g., Alvarez & Cavanagh, 2004). Alternatively, extrinsic feature combinations could also have influenced WM performance by consuming more available “object slots” in WM to correctly represent the to-be-remembered information (Zhang & Luck, 2008). More representations have to be retained if disjunct extrinsic features have to be retained, compared to inherent intrinsic features. However, with respect to the maintenance phase, the electrophysiological data calls the interpretations into question.

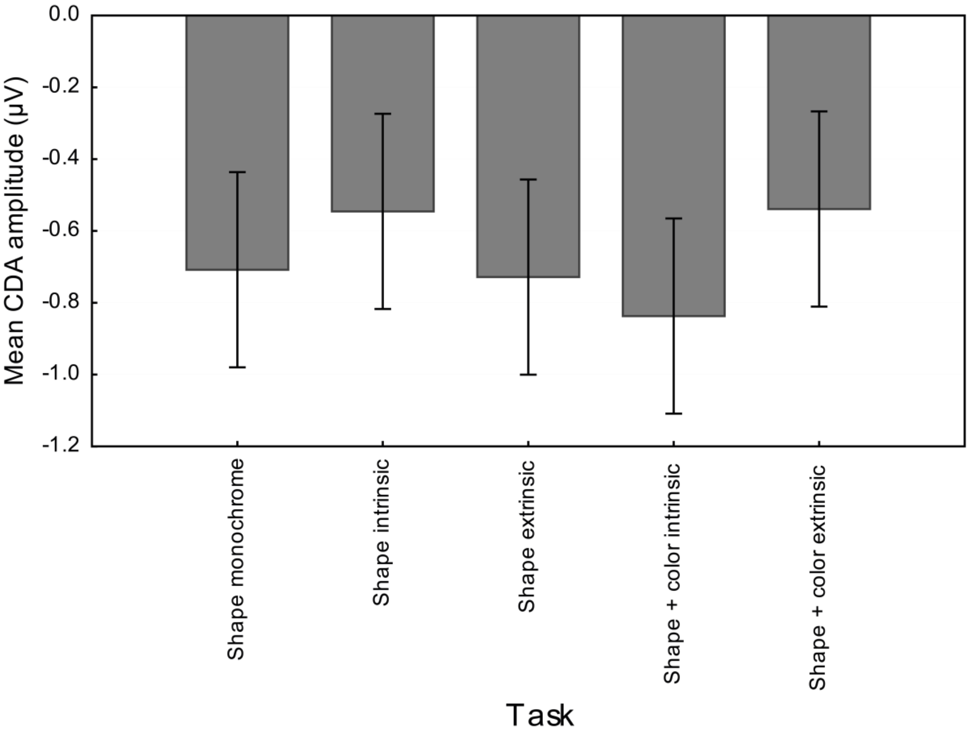

Figure 17: Mean CDA amplitudes across all tasks and stimulus types. Whiskers show 95% within-CIs for the means corrected according to Jarmasz and Hollands (2009).

4.4.2 NEUROPHYSIOLOGICAL CORRELATES FOR RETAINING INTRINSIC AND EXTRINSIC INFORMATION

With respect to intrinsic information, we expected the CDA to be similar for conditions where participants intentionally store shape-color associations and conditions where only the shape features are task-relevant. As indicated by previous studies, intrinsic information should be integrated into the WM representation rather unintentionally without causing observable demands on the WM system (e.g., Ecker et al., 2013). The observed lack of difference between intentionally and non-intentionally processed intrinsic information meets these expectations. Critically, neither the amplitude for intentionally nor unintentionally stored intrinsic associations varies from the monochrome single feature condition. With respect to the processing of extrinsic information, we will come back to this point later.

We assumed that extrinsic information is only represented in WM if the task demands it. Moreover, maintaining extrinsic information could be a more demanding process if individual representations or disjunct representations have to be retained (e.g., Ecker et al., 2013). More pronounced CDA amplitudes were thus expected for intentionally stored extrinsic shape-color associations compared to conditions where only the shape is task-relevant but not the extrinsic color. This was not observed: CDA amplitudes were similar for monochrome stimuli and extrinsic stimuli when only the shape was relevant; this is in line with our expectations as extrinsic information should only be intentionally engaged (Zimmer & Ecker, 2010). However, CDA amplitudes did not further increase when extrinsic feature combinations were intentionally stored. This contradicts the assumption that extrinsic object feature associations are represented as disjunct entities.

Moreover, retaining intrinsic and extrinsic feature association posed comparable demands during maintenance, as indexed by electrophysiological signals. The amplitude for intentionally stored extrinsic associations was not significantly more pronounced than the amplitude for intentionally stored intrinsic associations. Following the assumption that the CDA tracks a finite number of stored objects (e.g., Quak et al., 2018), it is thus possible that both intrinsic as well as extrinsic stimuli were represented in an integrated unit. With respect to studies suggesting that the CDA indicates maintenance demands, intrinsic and extrinsic shape-color associations pose comparable demands on the maintenance system (e.g., Luria et al., 2010), once transferred into a representation. Previous studies indicated that online integration of separate features is conceivable; for example Luria and Vogel (2014) found that separate stimulus features can be integrated into a common representation, given strong cues such as common fate. Similar effects were observed by Balaban and Luria (2016, Experiment 4). As alluded to earlier (see Chapter 2.3.4), the operationalization of extrinsic stimuli could have allowed for such an integration of disjunct extrinsic features into a common higher-order representation (Ecker et al., 2013). We interpret these findings as integrated rather than separate extrinsic representations are retained during a WM task. The maintenance demands of both stimulus representations appear to be no critical factor driving the processing difference between intrinsic and extrinsic stimuli in WM.

4.4.3 CONCLUSIONS AND CAVEATS

Behavioral performance indicates that the visual WM is influenced by feature load and intrinsic and extrinsic information influence WM performance to different extent. The present findings suggest that this influence is most likely not caused by extrinsic associations placing higher demands on the short-term retention process. Once transferred into a stable representation, both intrinsic and extrinsic shape-color associations can be integrated into representational entities. Findings from ERPs related to storage demands do not suggest that extrinsic associations are retained as separate (or disjunct) entities.

Contrary to previous studies (Gao et al., 2009; Luria et al., 2010; Luria & Vogel, 2011), mean CDA amplitudes did not differ depending on task-demands or stimulus type. One potential explanation for this is that the influence of informational load might not be observed under all conditions. For example, Luria and Vogel (2011) investigated maintenance processes during a change detection task where participants had to store only one stimulus (e.g., one color patch or one abstract shape). Retaining a single item might represent a singular condition where participants do not have to split available mental processes between items (see also the "solo" condition from Wilson et al., 2012). As assumed by Cowan (1999), although more stimuli can be held in an activated state, only one stimulus can be kept in direct focus of attention. In the present study, two stimuli had to be retained, suggesting that participants had to invest their attentional resources on both stimuli. This could have overshadowed observable effects of informational load.

Moreover, in a study from Luria et al. (2010) the CDA amplitude increased from set size two to four only for simple color patches. In contrast, the CDA did not vary for more complex stimuli (for similar results, see Gao et al., 2009). Although simple geometric stimuli were used in the present experiment, the implementation of the intrinsic-extrinsic dimension by adding a quadratic frame to the shape could have increased the complexity of the stimuli to an extent that prevented the observation of effects due to informational load. Clearly, further research, potentially with single stimulus retention (e.g., Luria & Vogel, 2011), is needed to contribute to this discussion.

Previous studies suggest that the CDA reflects the number of object representations retained in WM (see, e.g., Ikkai et al., 2010; Luria et al., 2016). The present study strengthens this position: although a significant negative waveform was observed across all conditions, we did not find this negativation to be influenced by factors like stimulus type or feature relevance. As set size was held constant in the present Experiment 3, a constant amplitude would be expected if the CDA represents the mere number of isolated objects (e.g., Ikkai et al., 2010; Luria et al., 2016). Our findings hence corroborate the assumption that the CDA tracks the number of represented integrated objects during multi-stimulus tasks.

5 EXPERIMENT 4: INTRINSIC AND EXTRINSIC INFORMATION PROCESSING DIVERGE ACCORDING TO TASK-DEMANDS

Behavioral data from Experiments 1 and 2 yielded only sparse evidence that processing differences for intrinsic and extrinsic bindings were due to a more demanding binding mechanisms for extrinsic features. Instead, attentional selection effects appear to influence intrinsic and extrinsic information processing. Ecker et al. (2013) argued that intrinsic feature processing is based on a rather involuntary perception-related process that integrates object features within an object token (Zimmer et al., 2006; Zimmer & Ecker, 2010). This object token can be compared with other perceptual input, what is again considered a rather automatic process (Treisman, 2006). On the other hand, processing of extrinsic objects features is discussed to be more deliberate, and—at least—two independent tokens in perception have to be associated in memory (Cabeza, 2006). In other words, intrinsic but not extrinsic feature information appears to be an obligatory part of the representation that is matched against the probe. In Experiment 4, we want to substantiate this processing difference between intrinsic and extrinsic feature integration in WM by applying an irrelevant change detection paradigm while simultaneously recording the electroencephalogram. The temporal resolution of the EEG allows for a specification of the time course of feature integration. If intrinsic but not extrinsic features are automatically integrated in WM, study-test changes to the former but not the latter should provoke electrophysiological mismatch effects, even if the intrinsic feature is task-irrelevant. Such mismatch effects can provide evidence that behavioral effects of study-test changes to irrelevant features result from early object processing and not later decision-making processes.

5.1 N2 AS AN INDICATOR OF MISMATCH

One suitable electrophysiological signal is the N2 mismatch effect of the ERP. Supplementary to RT or recognition accuracy, the frontal N2, a negative deflection about 200 ms after stimulus onset, is considered as an indicator of the perceived deviation of new information from a template that is currently represented in WM (Folstein & van Petten, 2008; Wang et al., 2004; Yin et al., 2012). While behavioral measures may be biased, for example, by decision-making processes (see, e.g., Fitousi, 2018, for a comparable discussion) or strategic effects (e.g., Peterson & Naveh-Benjamin, 2016), early electrophysiological measures should be less prone to such effects.

As introduced in Chapter 1.2.2.2, modulations of the N2 can be found for single and multiple stimulus displays (e.g., Gao et al., 2010), and different types of stimulus manipulations (such as deviating colors, Gao et al., 2010; shapes, Cui et al., 2000; numbers, Kong et al., 2000). The N2 is found most prominent over frontal electrodes (see Folstein & van Petten, 2008, for an extensive review), and this negative going wave may be larger for task-relevant than for task-irrelevant deviations from the mental template (Wang et al., 2004). However, for the scope of the present research, it is important to specify what "template" refers to.

A large body of research on the N2 has been used in the context of the oddball paradigm. There, "template" refers to the frequent stimulus that is some form of short-term memory experience (or even a formed long-term memory entry), for example a recurring tone (Pritchard, Shappell, & Brandt, 1991). For the given research question, sequential matching tasks—where participants indicate from trial to trial whether two subsequent stimuli are identical—might provide a more suitable approach to define the interpretation of the template. In a series of experiments, Wang et al. (2003) presented sequences of stimuli to the participants, while the electrophysiological signal was recorded. Each stimulus consisted of three features (orientation, color, and shape). Participants had to indicate whether two consecutive stimuli were identical or different. In three different conditions, participants had to either attend all stimulus features, only the color, or the color and the shape. Thus, in the latter two conditions, some of the object features were task-irrelevant, and the number of critical feature dimensions varied from three to one. If a stimulus feature was changed, the authors observed a negative peak around 270 ms most pronounced across frontal and central electrode sites after the onset of the second stimulus. Most important, the amplitude of the N2 was same across all change conditions, irrespective of how many features changed from stimulus one to stimulus two and how many features participants had to attend. In a second study, Wang et al. (2004) again presented participants colored shapes in a sequential matching task and participants either attended only the color, only the shape, or the combination of both features. From the first to the second stimulus, no, one, or both features could change. If participants attended only to a single feature dimension, the N2 elicited by feature changes followed some form of gradient: the N2 was largest if all stimulus features were changed, smallest if no feature was changed, and approximately intermediate if the task-irrelevant feature was changed. Similarly, Yin et al. (2011) found that the amplitude of the N2 was modulated by attention to features even at longer retention intervals (4000 ms). These results suggest that the manifestation of the N2 mismatch signal is influenced by attentional processes.

With “template”, we, thus, refer to the representation that is used by the observer to answer the question whether new information is same or changed to studied information.

If intrinsic and extrinsic information differ in the ease of representation, the N2 should be particularly suited to investigate this distinction. As intrinsic information is assumed to be involuntarily represented, we should be able to observe an N2 mismatch signal for changed intrinsic information independent from whether attention is directed toward the corresponding feature or not. However, if extrinsic information processing is a more deliberate process, the expression of the N2 for extrinsic features should depend on task-demands. If the extrinsic information is relevant to the task, attention should be directed toward the extrinsic feature and the feature is transferred into a WM representation. If the extrinsic information is, however, not relevant to the task, the extrinsic information should not become a component of the template used to evaluate the probe. As a consequence, the N2 should be less pronounced for task-irrelevant extrinsic features compared to task-relevant.

5.2 OLD-NEW-EFFECTS FOR INTRINSIC AND EXTRINSIC INFORMATION

Besides the N2, two further event-related EEG components exist that tentatively vary with study-test changes to task-irrelevant information in WM. A number of previous studies have compared intrinsic and extrinsic object feature retrieval in LTM. These studies were conducted within the dual-process framework of recognition memory. According to this framework, recognition can be based on two processes: the recollection of specific episodic details associated with the information, or the evaluation of familiarity with the encountered information (for a review, see, e.g., Yonelinas, 2002).

As alluded to in Chapter 1.4.2, in LTM research, intrinsic and extrinsic representations have been found to be differentially associated with familiarity and recollection, respectively. In LTM studies, intrinsic and extrinsic changes have been found to affect neurophysiological signals assumed to reflect the processes of familiarity and recollection (see Zimmer & Ecker, 2010, for a review). Ecker et al. (2007a) and Ecker et al. (2007b) found that the ERP signature of automatic familiarity—an early mid-frontal old-new effect with ERPs to old items going more positive than to new items around 300 to 500 ms after stimulus onset (FN400)—was reduced by task-irrelevant intrinsic color changes from study to test, whereas this modulation was not consistently observed with extrinsic study-test changes. The authors concluded that intrinsic but not extrinsic features are involuntarily processed during recognition. The ERP signature of recollection—a later parietal old-new effect with a more positive deflection for old compared to new items approximately 500 to 800 ms after stimulus onset (late positive complex, LPC)—showed a similar pattern in Ecker et al. (2007a; also see Groh-Bordin, Zimmer, & Ecker, 2006): Changing a shape in the background (an extrinsic feature) reduced the LPC old-new effect only if it was task relevant but not otherwise. These findings led the authors to suggest that recollection is driven by a higher-level object-plus-context representation that incorporates a lower-level object representation that drives familiarity with (task-relevant) extrinsic context features (however, Ecker et al., 2007b, did not find any LPC effect in a similar task, neither for intrinsic nor extrinsic stimuli). Thus, as argued by Zimmer and Ecker (2010), intrinsic and extrinsic representations subserve familiarity and recollection to different extents.

Importantly, these old-new effects are not restricted to LTM. ERPs related to familiarity and recollection have also been found during WM tasks. For example, Ko et al. (2014) tested memory for color patches in a single probe WM task. For younger adults, early (FN400-like) and late (LPC-like) old-new effects for correctly classified test stimuli were observed. Furthermore, early old-new effects have been found to be influenced by the perceptual similarity of shape-color associations between study to test in a visual WM task (Saiki, 2016) and congruence in sequential study displays (Crites, Delgado, Devine, & Lozano, 2000; Danker et al., 2008). It should be noted, however, that FN400 effects in WM do not seem to arise with certain types of stimuli; for example, Danker et al. (2008) found no FN400 for spatial locations or unnamable stimuli, whereas they did find an LPC for a broad range of stimuli (see also Ko et al., 2014). It might thus be reasonable to assume that the effects of intrinsic and extrinsic feature processing observed in LTM also manifest in old-new effects during WM tasks (for a comparable position, see Zimmer, 2008).

To sum up, neural correlates related to the processing of visual WM representations should differ for intrinsic and extrinsic feature information according to task demands. While signals related to extrinsic feature processing should only be observed if the features are task-relevant, intrinsic information should be integrated in WM representations by default even if not task-relevant. To test this, we used a change detection task under two conditions: in the direct test condition, all features of an object (i.e., shape-color association) were task-relevant; in the indirect test condition, only the shape of an object relevant (i.e., object color was task-irrelevant). Color was either an intrinsic surface-feature of the shape or an extrinsic feature of a quadratic frame surrounding each shape (following Ecker et al., 2007b; Staresina & Davachi, 2009). For the shape-color association, we expected (a) better memory for color with intrinsic than extrinsic stimuli; (b) an N2 mismatch effect associated with any study-test feature change (i.e., a more negative waveform for changed vs. unchanged test items); and (c) an FN400 old-new effect associated with any study-test feature change (i.e., a more positive waveform for unchanged vs. changed test items). For the shape-only condition, we expected (d) task-irrelevant color changes to lead to performance costs[6] that are larger for intrinsic than extrinsic items; (e) an N2 mismatch effect for task-irrelevant changes to intrinsic color (that is smaller or absent for extrinsic color); and (f) an FN400 old-new effect for task-irrelevant changes to intrinsic color (that is smaller or absent for extrinsic color). As previous results allow less clear-cut predictions for the LPC, we speculated that changes to extrinsic features should influence this effect only if they are task-relevant, while intrinsic feature changes might modulate the LPC irrespective of task relevance to the same extent that they modulate the FN400 (see Zimmer & Ecker, 2010).

5.3 METHODS

The experiment used a fully crossed 2 (test type: direct, indirect) × 2 (stimulus type: intrinsic/extrinsic) × 3 (change type: new shape/new color/no change) repeated-measures design. Comparable to Experiment 1, in the direct test, both item features were relevant; in the indirect test, shape was task-relevant but color was task-irrelevant. Color was either an intrinsic part of the shape or an extrinsic part of the surrounding frame. Importantly, trials with color changes from study to test called for different responses in the two tasks: During the direct test, color changes were non-match trials; in the indirect task, color-change trials were match trials.

5.3.1 PARTICIPANTS

A total of 26 German right-handed undergraduate non-psychology students were recruited at Saarland University. Data from two participants was not analyzed due to technical errors. The final sample consisted of 24 participants (14 females, 10 males), with age ranging from 18 to 29 years ($M = 23.42$ years, $SD = 2.81$).

All participants reported normal or corrected-to-normal vision, no clinical diagnose of migraine or epilepsy, no history of neurological disorders (within the last 5 years), and no current intake of pharmaceutical that could influence RT. After the nature of the study was explained, participants provided written informed consent after reading an ethically approved information sheet. Participants received a monetary compensation of €8 per hour. The study was approved by the Ethics Committee of the Philosophical Faculty III Empirical Human Sciences at Saarland University.

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[6] That is, prolonged RTs and/or reduced memory accuracy.

Participants mean score in digit symbol substitution test (adapted from Wechsler, 2008) to estimate processing speed was *M* = 65.96 (*SD* = 10.08). The mean score in the multiple-choice knowledge test (adapted from Lehrl, 1977) to estimate crystalized intelligence was *M* = 30.38 (*SD* = 2.34). The results suggest that the sample performed in a comparable range to younger adults assessed in previous Experiments 1 to 3. To estimate components of WM capacity, participants solved the backward digit span test, adapted from Wechsler (2008). Participants' mean score was *M* = 6.50 (*SD* = 2.28), suggesting that the sample performed rather well compared to other studies (e.g., Grégoire & van der Linden, 1997).

5.3.2 MATERIALS AND APPARATUS

The same set of nine simple geometric shapes as in Experiment 2 and 3 was used. Each shape was encased by a quadratic frame. For intrinsic stimuli, the shape was colored in one of seven colors: blue (RGB values in parentheses; 50, 78, 143), cyan (0, 255, 255), green (0, 153, 51), yellow (255, 255, 0), red (255, 0, 0), purple (255, 0, 255), and brown (163, 73, 164); the surrounding frame was white (255, 255, 255). For extrinsic stimuli, the shape was white and the frame colored. The structurally identical intrinsic and extrinsic stimuli only differed in the distribution of the color. All stimuli were presented on a black (0, 0, 0) background. The shapes subtended a visual angle of 1.49° × 1.49° and the surrounding frame subtended 3.54° × 3.54° of visual angle. The width of the frame was 0.28° of visual angle, thus creating a spatial separation between the shape and the frame. The experiment was presented on a 23-inch flat screen with a resolution of 1,920 × 1,080 pixel at a refresh rate of 60 Hz. Participants were seated in front of the screen at an approximate viewing distance of 60 cm.

5.3.3 PROCEDURE

The trial structure is illustrated in *Figure 18*. Each trial started with a fixation cross presented at the center of the screen, which was visible until the offset of the memory display. After a time interval of 400 to 600 ms (with random jitter), a task cue was presented for 800 ms and then disappeared. In the direct test, the cue was "BEID" (short for "Beides", the German expression for "both"), indicating that the shape-color association was task-relevant; in the indirect test, the cue was "FORM" (the German expression for "shape"), indicating that only the shape information was task-relevant. After an 800 ms post-cue interval (to allow for proper task preparation), the study array was displayed for 200 ms. The study display comprised of two stimuli were presented on an invisible circle subtending 7° of visual angle around the center of the screen. Positions were pseudo-randomly selected such that the two stimuli were always located opposite to each other in different half-field of the circle. Each stimulus consisted of a different color and shape, with no repetition allowed within the memory array. Following a retention interval of 900 ms, a single probe was presented in the center of the screen. A central probe was chosen to minimize possible influences of location cues (see Brown & Brockmole, 2010; van Geldorp et al., 2015). In the direct test, participants decided whether or not the probe matched an item from the memory array on both feature dimensions. In the indirect test, participants decided whether the presented shape matched a shape from the memory array. Responses were given on a Cedrus response pad (RB-834, Cedrus Corporation, San Pedro, California). The mapping of "match" and "mismatch" decisions to the response hands was counter-balanced across participants. The test array was presented until a response was given or for a maximum of 2,500 ms; it was followed by an inter-trial interval of 1,500 ms. Both accuracy and response speed were emphasized.

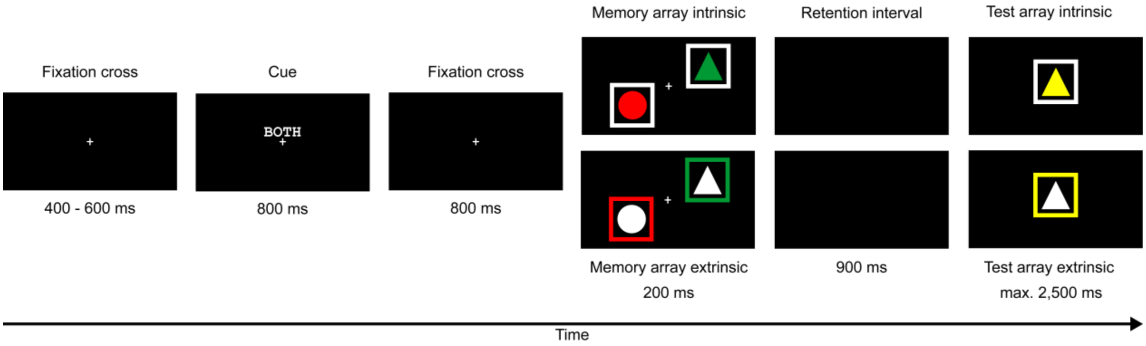

Figure 18: Schematic illustration of the trial structure of Experiment 4, not drawn to scale. A "`FORM`" (shape) cue was associated with the indirect test; a "`BEID`" (both) cue was associated with the direct test. In the example, a "change" trial is depicted (i.e., the test probe has a color not presented during the study array and the correct response is thus "new"). In the shape-only condition, the trial would reflect a "no change" condition (i.e., the test probe is a studied shape; the color change is irrelevant and the correct response is thus "old").

There was a total of 640 trials; half the trials (320) used intrinsic and extrinsic stimuli, respectively. For each stimulus type, half the trials (160) belonged to the direct test and the indirect test, respectively. For each test condition, half the trials (80) required a match response and half a change response. In the direct test condition, half the trials (40) featured a shape changes and half a color change. In the indirect test condition, half the no-change trials (40) featured a (task-irrelevant) color-change. To minimize task-switching costs, trials of each test condition (direct/indirect) were blocked in short sets of at least eight consecutive trials. Participants were able to take a self-paced break every 80 trials. There were 32 practice trials that were not included in analyses. Including the EEG preparation, Experiment 4 lasted 2 to 2.5 hours.

5.3.4 ELECTROPHYSIOLOGICAL RECORDING AND ANALYSIS

The EEG signal was recorded from 32 active Ag/AgCl electrodes (Acticap, Brain Products, Munich, Germany) mounted on an elastic cap. Electrode locations from the International 10-20 System (Fp1, Fp2, F7, F3, Fz, F4, F8, C3, Cz, C4, P3, Pz, P4, O1, O2) was used in addition to nonstandard locations mainly at frontal and parietal sites (FC5, FC1, FC2, FC6, CP5, CP1, CP2, CP6, T7, T8, P7, P8, PO7, PO8). The ground electrode was mounted on AFz. All signals were recorded with a left-mastoid reference and later re-referenced offline to linked mastoids. Vertical electrooculogram and horizontal electrooculogram were monitored with one electrode centered below the right eye and one electrode at the outer canthus of the right eye. All impedances were kept below 5 kΩ. Signals were amplified with a DC-coupled amplifier (Brain Amps, Brain Products, Munich, Germany) and recorded with a sampling rate of 1000 Hz.

Preprocessing and data analyses were conducted using BrainVision Analyzer (Version 2.1.1.357; Brain Vision, LLC). The continuous signal was down-sampled to 512 Hz, filtered off-line with a Notch-filter at 50 Hz and a high-pass filter of 0.1 Hz, 24 dB/octave, as well as a low-pass filter of 30 Hz, 12 dB/octave, as recommended by Luck (2014). The EEG signal was segmented into epochs from -200 ms to +800 ms locked to the onset of the test display. Erroneous trials or trials with missed responses were neglected. Epochs were baseline corrected using the -200 to 0 ms interval. Ocular blink artifacts were corrected according to Gratton et al. (1983); if fewer than 20 blinks were recorded for a participant, trials containing blinks were rejected instead of corrected. In addition, epochs containing artifacts not related to blinking (on average 7.94 % of the trials) were rejected before averaging based to the following criteria: maximal voltage step between two successive sampling points: 30 µV; maximal difference across an interval of 200 ms: 150 µV; maximum amplitude in the recording epoch: ±100 µV; lowest allowed activity within an interval of 100 ms: 0.5 µV.

Based on previous studies (Folstein & van Petten, 2008; Gao et al., 2010; Randall & Smith, 2011; Wang et al., 2003; Yin et al., 2011; Zhou et al., 2011) statistical analyses of the N2 focused on the frontal electrodes of the midline. To assess neural correlates to mismatch processing, a peak-to-peak analysis of P2 and N2 components was conducted. To this end, we identified local positive maxima within the time window from 150 to 250 ms post-stimulus-onset for the P2 amplitude and negative maxima from 200 to 330 ms for the N2. Differences between these peak amplitudes were computed for each condition and averaged across participants to quantify the N2 mismatch effect. Linear trend analyses of the N2 mismatch effect yielded that N2 mismatch effects were largest at Fz, smaller at Cz and smallest at Pz, for both, the direct test, with $F(1, 23) = 32.60$, $p < .001$, $\eta_p^2 = .59$, and the indirect test, with $F(1, 23) = 27.14$, $p < .001$, $\eta_p^2 = .54$; hence, it was decided to focus the analyses on Fz, following Gao et al. (2010), Yin et al. (2011), and Yin et al. (2012).

It was planned to focus the analysis of old-new effects on the time window of 300 to 500 ms post-probe onset for the FN400, and 500 to 800 ms for the LPC, as suggested by previous studies (Curran, Tepe, & Piatt, 2006; Danker et al., 2008; Friedman & Johnson, 2000; Zimmer & Ecker, 2010); however, as in Ecker et al. (2007b), no LPC was observed (see *Figure 19* and *Figure 20*; a supplementary analysis showing no effect of change type on ERPs in the time interval of the LPC can be found in the Appendix 2); as a consequence, based on visual inspection, analysis focused on the latency of a P3-like positive component that was modulated by change type, which offers an analysis that is complementary to the FN400 analysis. For FN400-like component, in the direct test, old-new effects were calculated as difference waves between no-change and change (new shape and new color, respectively) conditions in four regions of interest (ROI): anterior left (F3, FC1, FC5), anterior right (F4, FC2, FC6), parietal left (CP1, CP5, P3), and parietal right (CP2, CP6, P4). For the indirect test, difference waves were calculated between no-change and shape-change, as well as between the irrelevant color-change and the shape-change conditions.

5.4 RESULTS – BEHAVIORAL DATA

Similar to previous Experiments 1 to 3, a trial exclusion procedure prior to averaging resulted in the exclusion of 3.71% of the behavioral data (Hoaglin et al., 1986; Hoaglin & Iglewicz, 1987). Dependent variables were recognition accuracy and RT. As RTs were still not normally distributed, analyses on RTs were based on log10-transformed data, using only trials with correct responses. As results did not differ qualitatively and for ease of comprehension, we report descriptives based on the untransformed RT data. Analyses on RTs only incorporate trials with correct responses. If homogeneity of variances was violated during statistical analyses, Greenhouse-Geisser-corrected degrees of freedom are reported. Follow-up analyses using pairwise comparisons were Bonferroni-corrected if needed, as indicated by the subscript. *Table 6* shows the mean accuracy and RTs across all conditions that served as the basis for the data analyses.

Table 6: Mean accuracy scores (ACC) and mean response times (RT) in the direct test and indirect test in Experiment 4

Task	Stimulus type	Change type	ACC (*SD*)	RT (*SD*)
Direct test	Extrinsic	New color	.94 (.06)	690 (139)
		New shape	.95 (.06)	693 (152)
		No change	.91 (.09)	635 (128)
	Intrinsic	New color	.96 (.05)	674 (165)
		New shape	.93 (.07)	688 (124)
		No change	.93 (.06)	635 (128)
Indirect test	Extrinsic	Irrelevant new color	.90 (.07)	654 (144)
		Relevant new shape	.96 (.04)	685 (167)
		No change	.95 (.06)	620 (119)
	Intrinsic	Irrelevant new color	.87 (.08)	682 (134)
		Relevant new shape	.96 (.03)	662 (133)
		No change	.96 (.07)	616 (113)

Note. ACC = accuracy; *SD* = standard deviation; RT = response time.

5.4.1 DIRECT TEST

Memory performance on recognition accuracies for intrinsic and extrinsic shape-color associations was compared for each change type in a 2 × 3 repeated-measures ANOVA with factors stimulus type (intrinsic, extrinsic) and change type (new color, new shape, no change). The analysis yielded a main effect of stimulus type, $F(1, 23) = 7.05$, $p = .014$, $\eta_p^2 = .24$, which was qualified by a significant interaction of stimulus type and change type, $F(2, 46) = 5.00$, $p = .011$, $\eta_p^2 = .18$. No significant main effect of change type was observed, with $F(2, 46) = 1.46$, $p = .243$, $\eta_p^2 = .06$. To clarify, a separate 2 × 2 repeated-measures ANOVA with factors stimulus type (intrinsic, extrinsic) and change type (new color, no change) that resulted in a significant main effect of stimulus type, $F(1, 23) = 18.93$, $p < .001$, $\eta_p^2 = .45$, no main effect of change type, $F(1, 23) = 2.39$, $p = .136$, $\eta_p^2 = .09$, and no interaction, $F < 1$, indicated that the interaction was not caused by no-change and new color change trials. Instead, recognition performance for shape change further increased for extrinsic stimuli, but remained on the level of no-change trials for intrinsic stimuli (see *Table 6*).

RTs were analyzed in a 2 × 3 repeated-measures ANOVA with factors stimulus type (intrinsic, extrinsic) and change type (new color, new shape, no change). The analysis yielded a significant main effect of change type, $F(2, 46) = 15.14$, $p < .001$, $\eta_p^2 = .40$, a marginal significant main effect of stimulus type, $F(1, 23) = 3.41$, $p = .078$, $\eta_p^2 = .13$, and no significant interaction, $F(2, 46) = 1.43$, $p = .249$, $\eta_p^2 = .06$. Pairwise comparisons indicated that RTs to no-change trials, $M = 635$ ms, 95% CI [582, 688], $SE = 25$, were faster than RTs to color change trials, $M = 681$ ms, 95% CI [618, 746], $SE = 30$, with $p_{\text{Bonferroni}} = .003$, and shape change trials, $M = 691$ ms, 95% CI [634, 748], $SE = 28$, with $p_{\text{Bonferroni}} < .001$. RTs of shape and color changes were not significantly different, with $p_{\text{Bonferroni}} = .870$. While the detection of a changed feature influenced RTs, we found no indication that stimulus type influenced RT.

5.4.2 INDIRECT TEST

Our main focus in the indirect test data was on the costs of irrelevant color changes. These costs were computed by subtracting mean accuracy values and RT values, respectively, of match trials from those of irrelevant color change trials. Costs were thus expressed as negative decrements for accuracies and positive values (prolongations) for RTs.

A planned contrast indicated that accuracy costs were greater for task-irrelevant intrinsic color changes, $M = .09$, $SE = .015$, than for extrinsic color changes, $M = .06$, $SE = .010$, $t(23) = 1.92$, $p = .034$, $d_{\text{Cohen}} = .39$. The corresponding planned contrast on the log10-transformed RT data yielded the same result: RT costs were greater for task-irrelevant intrinsic color changes, $M = 66$ ms, $SE = 10$, than for extrinsic color changes, $M = 34$ ms, $SE = 11$, $t(23) = -2.73$, $p = .006$, $d_{\text{Cohen}} = -.56$.

5.5 RESULTS – ERP DATA

ERPs locked to the test stimulus onset of the direct test and the indirect test are presented in *Figure 19*. Difference waves showing old-new effects for both tests presented in *Figure 20*.

5.5.1 DIRECT TEST

5.5.1.1 N2 analyses

Mean peak-to-peak differences for the direct test from P2 (mean latency across conditions: $M = 204$ ms, $SD = 28$ ms) to N2 (mean latency across conditions: $M = 260$ ms, $SD = 37$ ms) are presented in *Figure 25*. A 2 × 3 repeated measures ANOVA with factors stimulus type (intrinsic/extrinsic), and change type (no change/new shape/new color) on the mean N2 mismatch signal at Fz yielded a main effect of change type, $F(2, 46) = 22.24$, $p < .001$, $\eta_p^2 = .49$, with no other significant main effects or interactions (all Fs < 1). Pairwise comparisons indicated that amplitude differences were largest for shape changes, $M = -9.78$ µV, 95% CI [-12.31, -7.24], $SE = 1.226$, followed by color changes, $M = -8.541$ µV, 95% CI [-10.66, -6.43], $SE = 1.022$, and smallest for no-change trials, $M = -6.98$ µV, 95% CI [-8.84, -5.11], $SE = 0.902$, with all $p_{\text{Bonferroni}} < .013$. N2 mismatch signals were larger for shape changes than for color changes. That is, while the N2 mismatch effect was larger for shape changes than for color changes, it was similar for intrinsic and extrinsic stimuli.

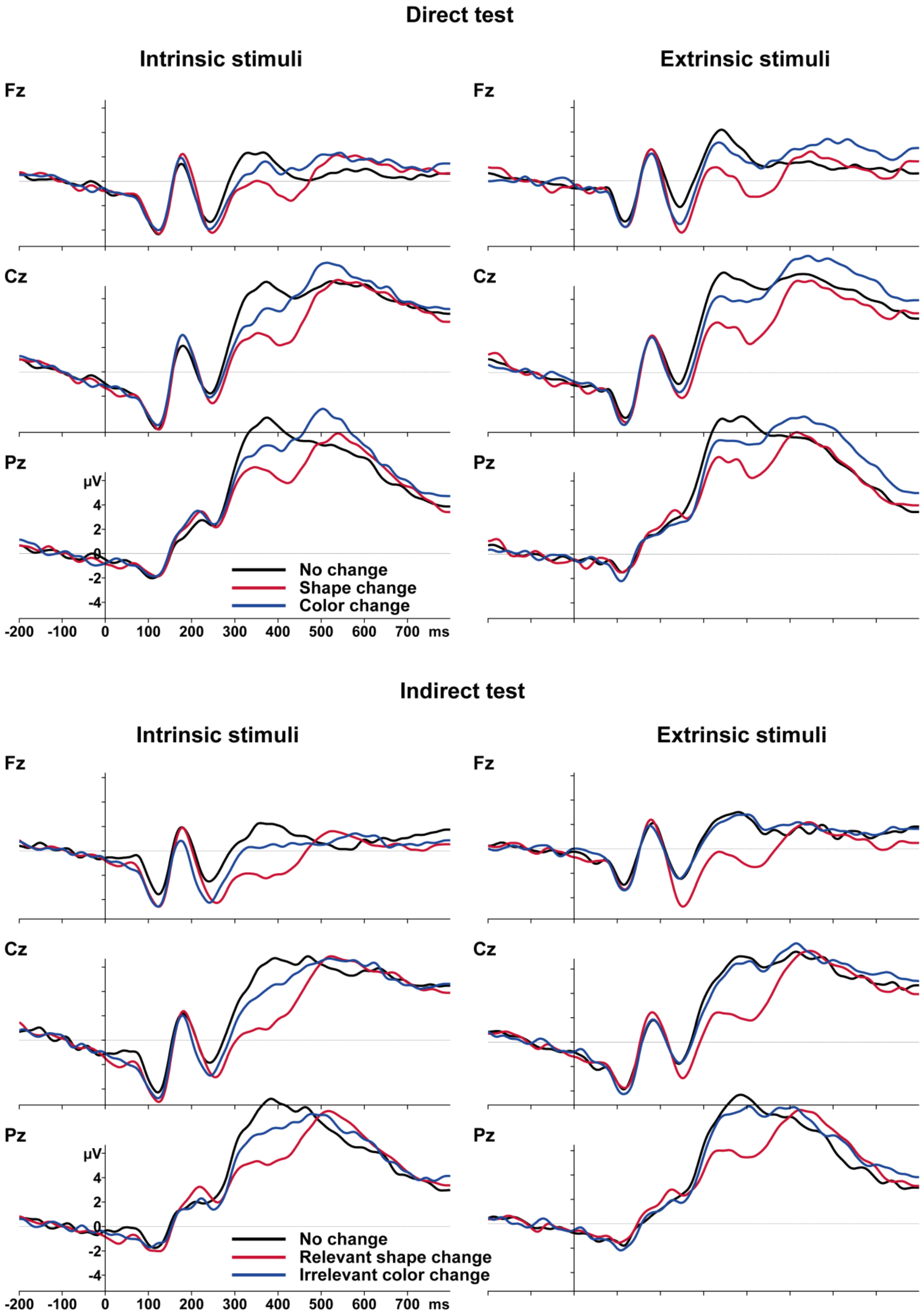

Figure 19: Grand-average waveforms for the three change conditions in the direct test (top) and the indirect test (bottom) for intrinsic and extrinsic stimuli. Waveforms are aligned to the probe stimulus onset. For illustrational purposes, data was filtered with a 25 Hz high-cutoff filter (12 dB/Oct), following recommendations from Luck (2014).

5.5.1.2 FN400-like old-new effects (300 to 500 ms) analyses

We conducted a 2 × 2 × 2 × 2 repeated-measures ANOVA on mean old-new differences in the 300 to 500 ms time window with factors area (frontal, parietal), hemisphere (left, right), stimulus type (intrinsic, extrinsic), and old-new effect change type (no change minus shape change, no change minus color change). There was a main effect of area, $F(1, 23) = 8.80$, $p = .007$, $\eta_p^2 = .28$, indicating that old-new differences were larger over parietal areas, $M = 1.72$ µV, 95% CI [1.24, 2.20], $SE = 0.231$, than frontal areas, $M = 1.21$ µV, 95% CI [0.71, 1.70], $SE = 0.239$. There was also a main effect of change type, $F(1, 23) = 21.78$, $p < .001$, $\eta_p^2 = .49$, indicating that old-new differences were larger for shape changes, $M = 2.31$ µV, 95% CI [1.77, 2.85], $SE = 0.261$, than for color changes, $M = 0.62$ µV, 95% CI [-0.01, 1.25], $SE = 0.305$. No other effects were significant (all Fs < 2.10, all ps > .156). Thus, intrinsic and extrinsic stimulus conditions did not differ, and old-new effects in terms of FN400-like ERP waveforms were enhanced for incongruent shapes than for incongruent colors if both features were task-relevant.

5.5.1.3 P3-like positive component analyses

For the direct test, the latency of the P3-like positive component appeared to be delayed by any type of study-test change (see *Figure 21*). This was confirmed by a 2 × 3 repeated-measures ANOVA on the peak latencies of the P3-like positive component measured at electrode site Pz (where the amplitude of the component was greatest) in the 300 to 600 ms time window (following Duncan et al., 2009), with factors stimulus type (intrinsic, extrinsic) and change type (no change, new color, new shape). The analysis yielded a significant main effect of change type, $F(2, 46) = 17.31$, $p < .001$, $\eta_p^2 = .43$, with no other significant effects, all $F < 1$. Pairwise comparisons indicated that the P3-like positive component peaked earlier in no-change trials, $M = 400$ ms, 95% CI [371, 429], $SE = 14$, than in color change trials $M = 469$ ms, 95% CI [438, 501], $SE = 15$, or a shape change, $M = 482$ ms, 95% CI [447, 518], $SE = 17$, both $p_{\text{Bonferroni}} < .001$. The latter two did not significantly from each other, $p_{\text{Bonferroni}} = .910$. Detecting a change delayed the P3-like late positive component compared to the detection of a no-change.

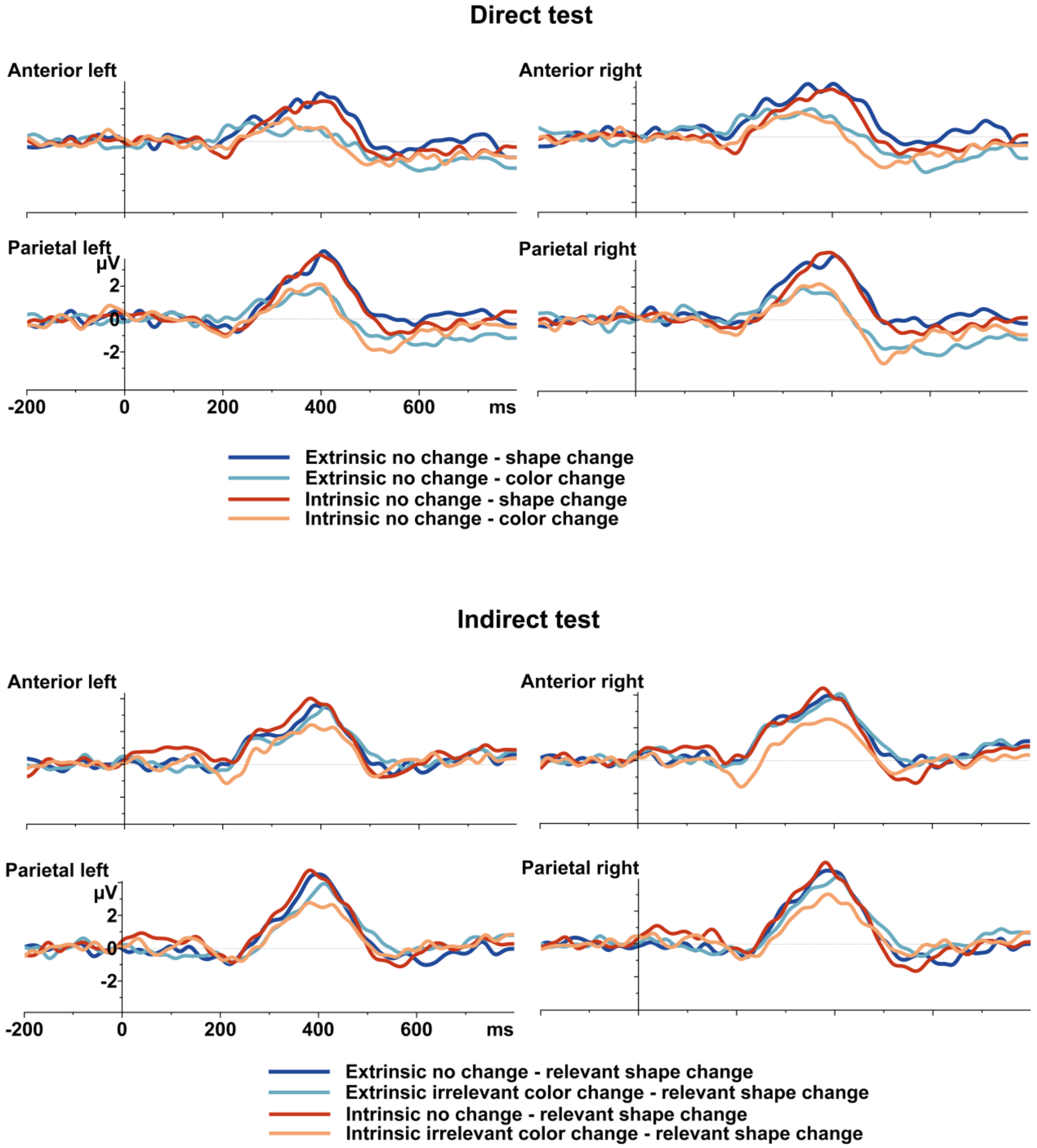

Figure 20: Grand-average waveforms illustrating old-new effects in the direct test (top) and the indirect test (bottom), across change types (shape change, color change) and stimulus type (intrinsic, extrinsic). Waveforms are aligned to test stimulus onset. For illustration purposes, data was filtered with a 25 Hz high-cutoff filter (12 dB/Oct), following recommendations from Luck (2014).

5.5.2 INDIRECT TEST

5.5.2.1 N2 analyses

Mean peak-to-peak differences for the indirect test from P2 (mean latency across conditions: M = 203 ms, SD = 28 ms) to N2 (mean latency across conditions: M = 257 ms, SD = 39 ms) at Fz are presented in *Figure 26*. A 2 × 3 repeated measures ANOVA with factors stimulus type (intrinsic, extrinsic), and change type (no change, new [relevant] shape, new [irrelevant] color), yielded a main effect of change type, $F(1, 23) = 8.09$, p =

.001, $\eta_p^2 = .26$, and no significant effect of stimulus type, $F < 1$. There was a significant interaction of stimulus type and change type, $F(1.60, 36.75) = 7.05$, $p = .005$, $\eta_p^2 = .24$. To scrutinize this interaction, pairwise comparisons were calculated for intrinsic and extrinsic stimuli across change types that indicated that for intrinsic stimuli, relevant shape changes, M = -8.24 μV, 95% CI [-10.45, -6.02], SE = 1.071, and irrelevant color changes, M = -8.48 μV, 95% CI [-10.37, -6.60], SE = .911, elicited negative potentials of comparable magnitude, p = .627, while both changes elicited significantly larger N2 signals than no-change trials, M = -7.28 μV, 95% CI [-9.05, -5.51], SE = .856, with corresponding ps < .048. For extrinsic stimuli, the pairwise comparisons revealed that relevant shape changes, M = -9.34 μV, 95% CI [-11.83, -6.84], SE = 1.204, $p < .001$, but not irrelevant color changes, M = -7.23 μV, 95% CI [-8.99, -5.47], SE = .849, $p < .741$, elicited an N2 signal that was significantly more negative than the no-change signal, M = -7.39 μV, 95% CI [-9.41, -5.38], SE = .972. That is, for intrinsic stimuli, irrelevant color changes evoked N2 signals comparable to relevant shape changes; for extrinsic stimuli, irrelevant color change evoked an N2 signal comparable to no-change trials.

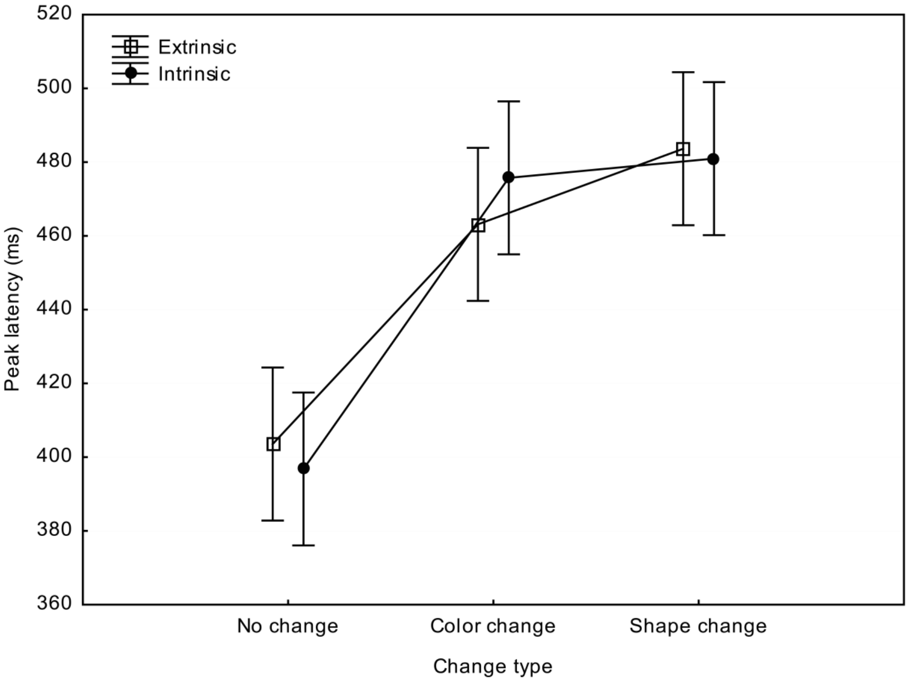

Figure 21: Mean peak latencies for the P3-like component in the direct test. Displayed are the latency peaks for each change type across intrinsic and extrinsic stimuli. Whiskers show 95% within-CIs for the means corrected according to Jarmasz and Hollands (2009).

5.5.2.2 FN400-like old-new effects (300 to 500 ms) analyses

In the direct test discussed earlier, we focused on the old-new differences across relevant change conditions. That is, we analyzed differences between the no-change condition (correct response: "old") and the color change and the shape change conditions (correct response: “new”), respectively. By contrast, in the indirect test, we used the shape change condition (rather than the no-change condition) as the comparison condition; that is, we analyzed differences between relevant the shape change condition (correct response: “new”) and the no-change condition and irrelevant change conditions (correct response: “old”), respectively. Thus, we ran a 2 × 2 × 2 × 2 repeated-measures ANOVA on condition difference in the 300 to 500 ms time window with factors area (frontal, parietal), hemisphere (left, right), stimulus type (intrinsic, extrinsic), and change type (no-change minus shape change, [irrelevant] color change minus shape change). This analysis revealed a significant interaction of stimulus type and change type, $F(1, 23) = 5.00$, $p = .035$, $\eta_p^2 = .18$, with no other effects reaching significance (all other $Fs < 3.65$, all $ps > .069$) Pairwise comparisons indicated that for extrinsic stimuli, the no-change minus shape change difference, $M = 2.72$ µV, 95% CI [2.07, 3.38], $SE = .316$, was not statistically differentiable from the (irrelevant) color change minus shape change difference, $M = 2.55$ µV, 95% CI [1.61, 3.50], $SE = .458$, $p_{\text{Bonferroni}} < .696$.

In contrast, for intrinsic stimuli, pairwise comparisons indicate that the no-change minus shape change difference, $M = 2.872$ µV, 95% CI [2.17, 3.62], $SE = .364$, was significantly larger than the (irrelevant) color change minus shape change difference, $M = 1.80$ µV, 95% CI [1.05, 2.56], $SE = .364$, $p_{\text{Bonferroni}} = .009$. In other words, no-change trials (i.e. “old” trials) resulted in a more positive-ongoing wave in the FN400 time-window compared to trials with task-relevant shape changes (i.e. “new” trials) in both intrinsic and extrinsic conditions. This old-new effect was reduced when shape change trials were compared to irrelevant color change trials, but only in the intrinsic not in the extrinsic condition.

5.5.2.3 P3-like positive component

Peak P3 latencies across conditions for the indirect test are presented in *Figure 22*. A 2 × 3 repeated-measures ANOVA on peak latencies with factors stimulus type (intrinsic, extrinsic) and change type (no change, new [relevant] shape, new [irrelevant] color) yielded a significant main effect of change type, $F(1.37, 31.56) = 13.70$, $p < .001$, $\eta_p^2 = .37$. The main effect of stimulus type, $F < 1$, and the interaction of stimulus type and change type, $F(2, 46) = 1.50$, $p = .235$, , $\eta_p^2 = .06$, were non-significant. Pairwise comparisons indicated no latency difference between no-change trials, $M = 421$ ms, 95% CI [394, 447], $SE = 13$, and (irrelevant) color change trials, $M = 440$ ms, 95% CI [413, 468], $SE = 13$, with $p_{\text{Bonferroni}} = .101$. However, the P3-like component was delayed significantly in relevant shape change trials, $M = 497$ ms, 95% CI [467, 528], $SE = 15$, with both $p_{\text{Bonferroni}} < .010$. Comparable to the direct test, the P3-like component in no-change trials peaked earlier than in change trials and the type of stimulus was irrelevant.

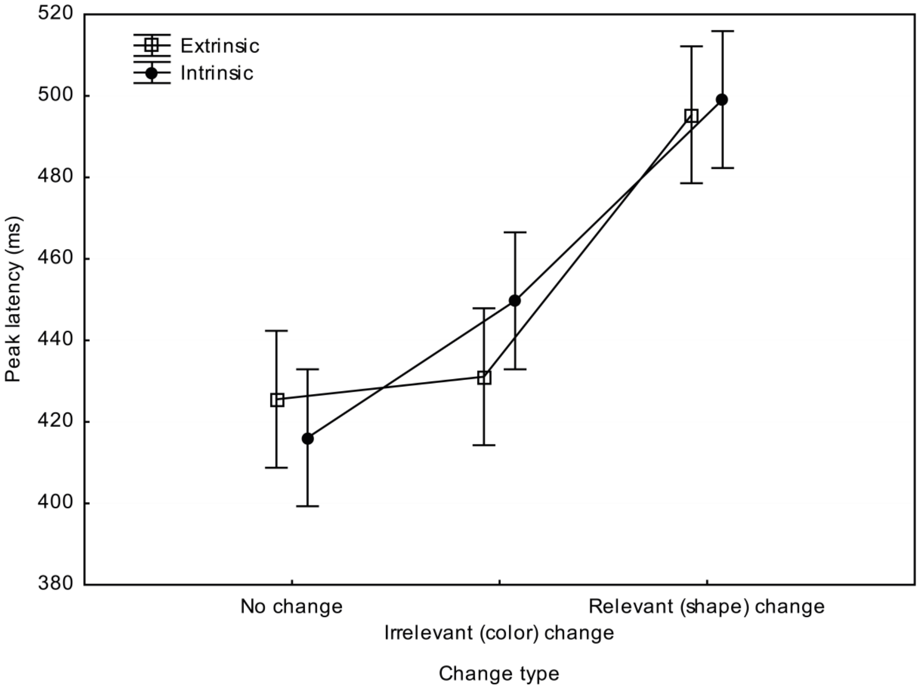

Figure 22: Mean latencies for the P3-like late positive component for the indirect test. Displayed are the latency peaks for each change type across intrinsic and extrinsic stimuli. Whiskers show 95% within-CIs for the means corrected according to Jarmasz and Hollands (2009).

Please note that in the indirect test, a task-irrelevant extrinsic color change elicited a similar P3-like positive component as a no-change trial. A task-irrelevant intrinsic color change, however, prolonged the latency of the P3-like positive component, although the interaction was not statistically significant. Most important, a prolongation would have been expected if interference had to be resolved, given that intrinsic feature information was assumed to be processed involuntarily. In fact, visual inspection revealed that the mean latency of the P3-like component lies “in between” the no-change and the shape change condition (see *Figure 22* for intrinsic stimuli). We noticed that the distribution of latency costs caused by the irrelevant color change compared to no-change condition (i.e. the numerical difference between the peak latency of the P3-like positive component for irrelevant color change trials and no-change trials) was a uniform normal distribution for extrinsic, but a bimodal distribution for intrinsic stimuli (see *Figure 23*). We hypothesized that the bimodal distribution could be the result of different procedural approaches of the participants: while some could have been able to completely ignore the color information (i.e., color was not represented at test and the task-irrelevant color change could have been processed as a “no-change” trial), this might not have been possible for other participants; as a consequence, interference had to be resolved in a potentially time-consuming control process prolonging the P3-like positive component peak.

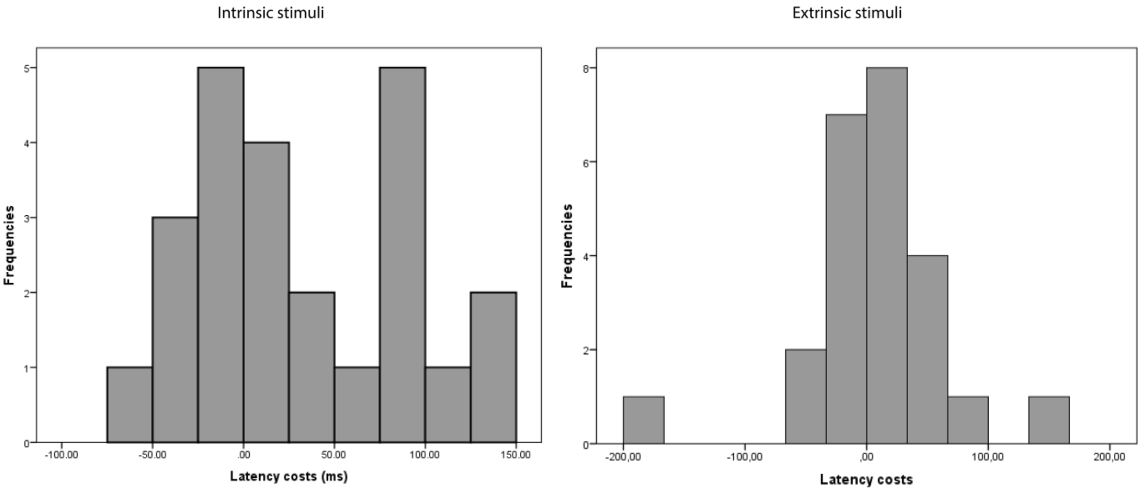

Figure 23: Latency costs in the P3-like late positive component for intrinsic (left panel) and extrinsic (right panel) task-irrelevant color changes compared to the no-change condition in the indirect test.

To test our hypothesis, we performed a median split according to the latency costs for intrinsic irrelevant color changes compared to no-change trials. We then compared the latencies for the P3-like positive component across all change conditions for each sub group (see *Figure 24*). A 3 × 2 mixed-measures ANOVA on the peak latencies with the within-subjects factor change type (no change, new [relevant] shape, new [irrelevant] color) and the between-subjects factor group (below median, above median) resulted in a significant main effect of change type, $F(1.19, 26.06) = 15.10$, $p < .001$, $\eta_p^2 = .41$, and a significant interaction of change type and group, $F(1.37, 31.56) = 5.19$, $p < .026$, $\eta_p^2 = .19$. There was no significant main effect of group, $F(1, 22) = 2.15$, $p < .156$, $\eta_p^2 = .09$. For the below median group, pairwise comparisons indicated that latencies in irrelevant intrinsic color change conditions, $M = 409$ ms, 95% CI [373, 445], $SE = 18$, were not significantly different to latencies in no-change conditions, $M = 424$ ms, 95% CI [387, 460], $SE = 18$, , with $p_{\text{Bonferroni}} = .340$, while latencies in relevant shape change conditions were significantly prolonged, $M = 489$ ms, 95% CI [445, 532], $SE = 21$, with both $p_{\text{Bonferroni}} < .019$. For the above median group, latencies in irrelevant intrinsic color changes conditions, $M = 491$ ms, 95% CI [454, 527], $SE = 18$, were significantly later than in no-change conditions, $M = 409$ ms, 95% CI [372, 445], $SE = 18$, with $p_{\text{Bonferroni}} < .003$, and comparable to latencies in relevant change conditions, $M = 510$ ms, 95% CI [466, 553], $SE = 21$, $p_{\text{Bonferroni}} > .99$. When the complete sample was divided according to the median for the latency costs in the P3-like positive component during irrelevant color change, significantly different latency patterns can be observed. The bimodal distribution of the peak latencies of the P3-like positive component could be the result of some participants processing the irrelevant change condition comparable to no-change trials, while some participants process it comparable to relevant-change trials[7].

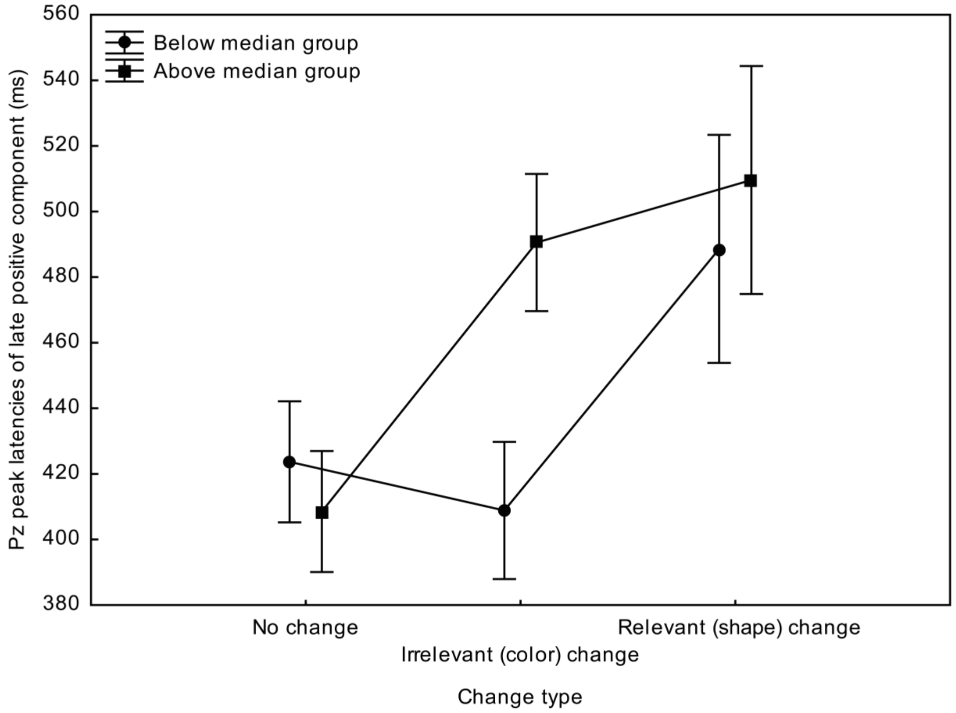

Figure 24: Mean peak latencies of the P3-like late positive component at electrode Pz in the indirect test for intrinsic stimuli across all change types. Whiskers show 95% within-CIs for the means corrected according to Cousineau (2005).

If some participants are able to completely ignore intrinsic color, they should show no N2 mismatch signal on trials with task-irrelevant color changes. Supplementary analyses showed that this was not the case. To test our assumption, we calculated the mismatch signal strength of the N2 for the irrelevant color change detection as the difference between the mean voltage of the N2 mismatch effect during irrelevant color feature changes and the no-change conditions. This was done for intrinsic and extrinsic stimuli. For intrinsic stimuli, an independent t-test revealed that the N2 mismatch signal strength was significantly *more* pronounced for the below median group, M = -2.10 µV, SE = 0.33, than for the above median group, M = -0.26 µV, SE = 0.33, with $t(22) = -3.93$, $p < .001$, $d_{\text{Cohen}} = -1.61$. In comparison, for extrinsic stimuli, an independent t-test revealed that the N2 mismatch signal strength did not significantly differ between both subgroups, $t(22) = -0.31$, $p = .762$, $d_{\text{Cohen}} = -0.13$, with M = 0.03 µV, SE = 0.79, for the below median group, and M = 0.33 µV, SE = 0.56, for the above median group. This suggests that task-irrelevant

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[7] For extrinsic stimuli, a 3 × 2 mixed-measures ANOVA on the peak latencies for the P3-like positive component with the within-subjects factor change type (no change, new [relevant] shape, new [irrelevant] color) and the between-subjects factor group (below median, above median) resulted in the known main effect of group and a significant main effect of change type, $F(2, 44) = 9.06$, $p = .001$, $\eta_p^2 = .29$. Most important, there was no significant interaction of change type and group, with $F < 1$, suggesting that the subgroups did not differ in their processing of extrinsic stimuli.

intrinsic color information was processed by all participants but the information could influence an earlier or later processing stage.

5.6 DISCUSSION

The aim of Experiment 4 was to corroborate previous findings of a processing advantage of intrinsic over extrinsic object features in visual WM. We assumed this effect to be driven by early object integration processes rather than later decision-making processes. To this end, we used a change detection paradigm featuring task-relevant shape changes and color changes that were either task-relevant or task-irrelevant depending on task conditions. Color was either an intrinsic or extrinsic feature of the stimuli. We recorded the EEG to investigate the early stages of target processing. To the extent that intrinsic but not extrinsic object feature information is obligatorily integrated during perception, we expected mismatch-related ERPs to be elicited by intrinsic color changes irrespective of feature relevance. By contrast, we expected mismatch-related ERPs to be elicited by extrinsic color changes only if color was task-relevant.

Overall, results supported these hypotheses: on a behavioral level, recognition performance for intentionally stored shape-color associations was overall better for intrinsic compared to extrinsic stimuli. Moreover, costs for task-irrelevant intrinsic color changes resulted in increased performance costs. Our investigation of early N2 mismatch effects and FN400-like old-new effects showed that only task-irrelevant changes to intrinsic stimuli elicited early signals of mismatch detection. This supports the notion that intrinsic but not extrinsic object information influences the early stages of target evaluation in an obligatory manner. The later LPC-like old-new effect typically found in recognition memory studies was not observed in the present Experiment 4, which limits the conclusions that can be drawn about more strategic memory and decision making processes. We did, however, observe latency shifts in a positive ERP component in the time window of the P3. Subgroup comparisons yielded first indications that this component appeared to be influenced by the earlier mismatch detection process. In sum, Experiment 4 provided electrophysiological support for a processing advantage of intrinsic over extrinsic stimuli influencing early stages of target processing.

5.6.1 INTENTIONAL PROCESSING OF INTRINSIC AND EXTRINSIC FEATURES

Behaviorally, recognition in the direct test was overall better for intrinsic compared to extrinsic shape-associations (replicating results from Experiments 1 to 3), although performance differences were rather small. Since extrinsic and intrinsic stimuli were structurally identical, with only color changing its distribution, the intrinsic color change detection advantage for intentionally stored features resembles previous findings of an object-based processing benefit: it is easier to attend to features integrated with the outline than to disconnected features (Xu, 2002b, 2002a).

In the direct test, both shape and color changes from study to test were task-relevant, and were thus arguably encoded into WM intentionally. In this case, intrinsic and extrinsic feature information influenced the early components of target evaluation to similar extents. Both intrinsic and extrinsic color changes elicited ERP effects associated with mismatch detection, with comparable N2 mismatch and FN400-like old-new effects for intrinsic and extrinsic color changes (see *Figure 25* and *Figure 26*, respectively). Both ERP effects did, however, differentiate between color and shape changes, with a more pronounced mismatch signal associated with shape compared to color changes.

This has two implications. First, the pattern suggests that intentionally processed intrinsic and extrinsic features are part of the WM representation used to evaluate the test stimulus, thus equally contributing to mismatch detection. This is in contrast to LTM research, where extrinsic information typically does not influence earlier components of recognition (see Zimmer & Ecker, 2010). In WM, however, extrinsic information can apparently influence earlier stages of target processing, potentially through a more top-down controlled process, as will be discussed below.

Second, the variation in mismatch signal amplitudes between shape and color changes might reflect different levels of neural activity needed to process the corresponding stimulus feature. For example, Corbetta, Miezin, Dobmeyer, Shulman, and Petersen (1990) found that neural activity can vary as a function of the attended feature, and argued that such variation might reflect differences in cognitive control associated with the processing of different features. In line with this, Wang et al. (2004) found enhanced N270 mismatch signals with task-irrelevant shape compared to color changes. If both features were however task-relevant, similar mismatch effects were observed. The authors speculated that features can attract attention to different extents, hence influences the cognitive control processes needed to solve a task. In the present study, the increased N2 mismatch signal for task-relevant shape compared to color changes could thus be the result of attentional modulation driven by conflict detection. It is, however, important to note that, in contrast to the study from Wang and colleagues (2004), location was not informative in the present Experiment 4. Speculatively, participants might have engaged a more controlled target evaluation, as proposed by Cowan et al. (2013): Due to the missing location feature, one feature (color or shape) might have functioned as some form of “anchor” to evaluate the whole location-independent representation against the test stimulus. This could have led to different attentional demands when processing an object feature. This interpretation would be in line with models suggesting that visual WM deals with different features at different processing stages (e.g., Alvarez & Cavanagh, 2008; Gao et al., 2013). Strikingly, the influence of stimulus type (intrinsic/extrinsic) seems to be task-dependent, as will be discussed in the context of processing task-irrelevant information.

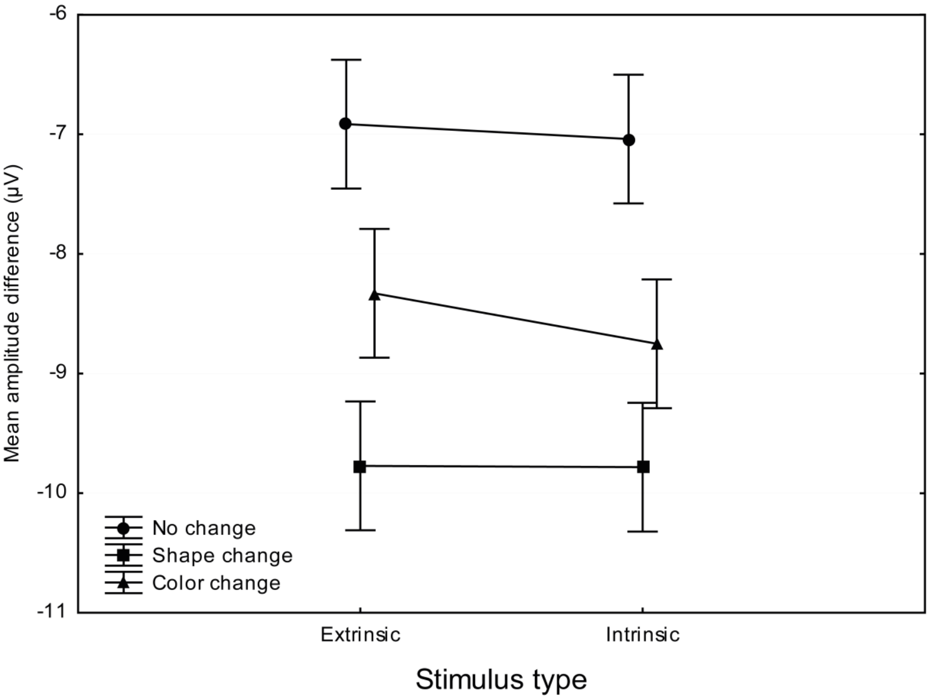

Figure 25: Mean Fz amplitude differences between P2 and N2 across stimulus and change types in the direct test. Whiskers show 95% within-CIs for the means corrected according to Jarmasz and Hollands (2009).

In contrast to the rather consistent findings on early electrophysiological potentials, data on later components yielded no pattern that resembled the expected parietal LPC-like old-new effect. Although this null-effect has to be treated with caution (since LPC-like old-new effects were already observed during WM tasks, e.g., Ko et al., 2014), previous studies on intrinsic feature processing in WM did not find and LPC-like old-new effect in older adults (Ko et al., 2014), and studies intrinsic and extrinsic feature processing in LTM did fail to find LPC-like old-new effects in younger adults (e.g., Ecker et al., 2007b). Although one could speculate that participants based their decision entirely on familiarity (FN400) and/or the absence of clear source memory (Herron & Rugg, 2003), it is not entirely clear why we did not observe consistent LPC-like old-new effects.

5.6.2 UNINTENTIONAL PROCESSING OF INTRINSIC AND EXTRINSIC FEATURES

Behaviorally, performance costs caused by task-irrelevant feature changes differed between stimuli: comparable to findings of the older sample in Experiment 1, RT prolongations and accuracy reductions were greater for task-irrelevant color changes to intrinsic compared to extrinsic stimuli. These behavioral results replicate findings from previous studies (e.g., Ecker et al., 2013).

In the indirect task, color information was task-irrelevant, so the task did not require the intentional processing of color information. In this case, ERPs differed for intrinsic and extrinsic color changes. For intrinsic stimuli, color changes elicited an N2 signal similar to the one elicited by shape changes. By contrast, the N2 in the extrinsic color change condition resembled the no-change condition (see *Figure 26* and *Figure 19*). To the extent that the N2 reflects mismatch detection (Folstein & van Petten, 2008; Yin et al., 2011; Zhou et al., 2011), this indicates that intrinsic but not extrinsic color information was part of the WM representation used to evaluate the target. The same pattern was observed for the FN400-like old-new effect. These findings strongly support our hypothesis that intrinsic but not extrinsic information is an obligatory part of the WM representation used to perform change detection.

In contrast to the direct test, N2 amplitudes were less distinguishable across conditions in the indirect test (see *Figure 26* below): While shape changes for extrinsic stimuli elicited a clearly more negative N2 compared to no-change trials, this effect was less pronounced for intrinsic items. This fits the assumption that intrinsic information is obligatorily represented at test: processing of the *unchanged* task-irrelevant color information leads to a “match” signal, thus reducing the N2 mismatch signature. This match signal will be stronger for intrinsic compared to extrinsic stimuli, for which the color information is less available. The fact that there was no N2 difference between no-change and extrinsic color-change conditions, despite the significant behavioral costs associated with irrelevant extrinsic color change, suggests that behavioral responses were also influenced by later decision making processes (for a broader discussion of effects on decision making, see, e.g., Hyun et al., 2009). At this point, however, further research is needed to clarify, why this was not reflected in the ERP data.

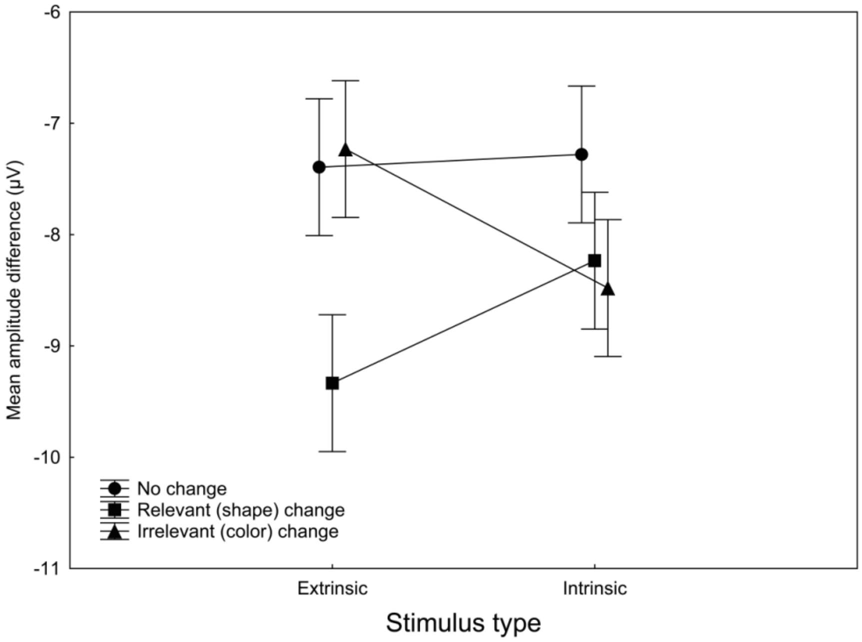

Figure 26: Mean Fz amplitude differences between P2 and N2 across stimulus and change types in the direct test. Whiskers show 95% within-CIs for the means corrected according to Jarmasz and Hollands (2009).

Although the influence of irrelevant intrinsic feature changes on early ERPs related to mismatch detection was clear-cut, influence on later potentials was less apparent, as discussed for the direct test. However, the positive component in the time window of the P3 could have overshadowed the observation of LPC-like old new effects. Peak latencies of the P3-like positive component were delayed for task-relevant shape changes compared to no-change trials. This is in line with previous findings suggesting that the amplitude and/or latency of the posterior-parietal P3 can by influenced by numerous factors related to change detection, such as categorization difficulty (e.g., Courchesne, Hillyard, & Courchesne, 1977; see also Polich & Kok, 1995) or matching requirements (e.g., Nieuwenhuis, Aston-Jones, & Cohen, 2005; Ullsperger, Metz, & Gille, 1988).

An unexpected finding was that latencies of the P3-like positive component were bimodally distributed for task-irrelevant intrinsic but not extrinsic color changes. This difference was unlikely the result of some participants being able to completely ignore the task-irrelevant intrinsic color change, as indicated by the N2 mismatch effect (participants with a short P3 latency had an *enhanced* N2 mismatch signal). The finding contradicts the assumption that a prolonged P3 latency reflects some form of time demanding interference resolution. It could, however, be the result of two different strategies: some participants could have adapted a more proactive approach (see, e.g., Braver, 2012), trying to actively suppress task-irrelevant information. Encountering a task-irrelevant intrinsic color changes leads to a pronounced early mismatch signal that can influence the execution of later components argued to subserve target evaluation such as the P3-like positive component that was found to be related to change detection in the present Experiment 4. However, we still found a RT delay, so that further processes must be assumed that influence the execution of the behavioral response. As noted above, no clear effects regarding late ERP components were observed; future research could show whether early mismatch signals affect later ERPs of more conscious retrieval operations in WM, such as the LPC (Ko et al., 2014).

Participants with a more reactive strategy could have followed a solution process were task-irrelevant information was processed at later stages, as participants could not have tried to actively suppress any task-irrelevant information. As a potential consequence, task-irrelevant information was not processed with high priority at early stages; however, findings indicate that intrinsic information was obligatory processed, hence the information influenced the change detection process at a later time window. We speculate that this could have manifested in prolonged P3 latencies.

The unexpected observation that an enhanced early mismatch signal (N2) is unlikely to be accompanied by a prolonged later component associated to change detection, lets us assume that an early mismatch signal does not necessarily carry the need to resolve interference. Instead, a clear-cut N2 mismatch signal could transport the need for increased cognitive control allowing the WM system to adapt to the situation (Cavanagh & Frank, 2014). If this mismatch signal is less distinct, the evaluation process “meanders” between the decision threshold (i.e., “same” or “different”; see drift diffusion models; e.g., Wagenmakers, van der Maas, & Grasman, 2007). Given previous findings that positive components in the time window of the P3 in WM are found to be associated to more conscious target evaluation (e.g., the decision whether a new incoming information is same or different to a template; Bledowski et al., 2006; Kok, 2001), the current results suggest that this processed can be supported by earlier components of mismatch detection. Part of the processing advantage of intrinsic over extrinsic features might thus be the role of early mismatch signals that contribute to a faster stimulus classification.

5.6.3 COMPARING INTENTIONAL AND UNINTENTIONAL PROCESSING

The comparison between the intentional and the unintentional processing of intrinsic and extrinsic feature information (direct and indirect test conditions) suggests that modulation of the focus of attention is of major importance for the processing differences between intrinsic and extrinsic information. Under indirect test conditions, attention was always directed to the shape; consequentially, intrinsic information could consistently contribute to evaluative processes, whereas no such influence was found for extrinsic information. In order for extrinsic information to influence the decision-making process, an intentional orientation toward the information was necessary as the extrinsic color is disjunct from the shape.

Potentially, intrinsic but not extrinsic information experiences some form of processing gain, as soon as the object is attended (see, e.g., Boynton, 2005). From visual search research, it is known that the allocation of attention can influence early visual processes (e.g., Müller, Reimann, & Krummenacher, 2003). Furthermore, in a stimulus detection experiment, Vogel and Luck (2000) found that the participants arousal as reflected by the attentional direction toward the stimuli influences the amplitudes of ERP components related to early stimulus processing (such as the P1). In line with this interpretation, no electrophysiological differences in early mismatch signals were observed for intrinsic and extrinsic stimuli if the shape-color association was intentionally heeded. Experiment 4, therefore, further stresses the assumption that—instead the execution of different or additional binding mechanisms—shifting the attention between object-inherent attributes to disjunct object-features could be one significant factor underlying the differences in intrinsic and extrinsic feature processing.

Besides Gestalt-factors, such as proximity or connectedness (e.g., Xu, 2006), the present study suggests that the object-benefit in WM is in part modulated by cognitive (attentional) control processes. Intrinsic information influences the mismatch or conflict evaluation detached from attentional resources. As argued by Ecker et al. (2013), extrinsic information, however, is only accessed if the task demands it. The present experiment corroborates this interpretation by revealing task-dependent contributions of extrinsic information to the evaluation of conflict.

It is important to note that the present experiment was not design to assess cognitive control. Therefore, future studies could use the task-switching paradigm (see, e.g., Kiesel et al., 2010, for a review) to examine whether stimulus types moderate the effects of switching costs. If extrinsic feature processing poses higher demands on early attentional processing than intrinsic feature processing, we would expect to see increased switch costs associated with former but not latter stimulus types.

5.6.4 CONCLUSION AND CAVEATS

Experiment 4 allows the following conclusions: (a) The distinction between intrinsic and extrinsic object features contributes to our understanding of object representation. (b) Intrinsic features are more readily integrated into WM representations than extrinsic features. (c) Processing of extrinsic features is more strongly associated with intentional information processing than intrinsic feature processing. (d) Intrinsic features have an increased likelihood of processing that is most likely the result of intrinsic feature information contributing to early mismatch detection effects. While this was found for intrinsic features under all processing conditions, extrinsic features can gain this benefit if intentionally processed. (e) Feature integration is not obligatory under all conditions; top-down adjustments of the focus of attention could be of critical importance for the processing difference between intrinsic and extrinsic information.

6 GENERAL DISCUSSION

Based on the question why the visual WM is sensitive to different types of object features, this dissertation project offers new insights to answer this question. While some positions consider the integrated objects as the unit of representation (e.g., Luck, 2008; Rensink, 2002; Vogel et al., 2001), others highlight the importance of features (e.g., Wheeler & Treisman, 2002) and their distribution across the objects for WM functioning: Although there is accumulating evidence that it is harder to retain multiple features in WM (e.g., Oberauer & Eichenberger, 2013), there is a memory benefit for features that originate from a common object (e.g., Fougnie et al., 2010; Xu, 2002b). However, it remains an open question of debate, what causes these pronounced differences in WM functioning.

We were interested in whether binding processes that influence the association of different stimulus types in LTM also influence WM. Based on the LTM framework of the type-token model (Zimmer & Ecker, 2010) introduced in Chapter 1.4.1, we aligned the experimental design along the basic assumption that two different binding processes are subject to differences in feature integration: We assumed that intrinsic binding is a rather *involuntary* or cost-free process provided via perception. Intrinsic features are, thus, rather obligatory *integrated* into an object token, which can again be compared with new input at no or minimal costs (Treisman, 2006; Zimmer & Ecker, 2010). In contrast, we assumed that extrinsic binding has to be *intentionally* engaged, as it associates independent tokens (Cabeza, 2006), rendering extrinsic binding a potentially *subsequent* process to intrinsic binding in WM (Delvenne & Bruyer, 2004). As a consequence, extrinsic feature bindings might represent some form of *higher-order representation* (Ecker et al., 2013). Moreover, intrinsic and extrinsic feature binding were assumed to be mediated via different brain regions (Zimmer & Ecker, 2010): while storage of extrinsic bindings is highly associated with activation in the *hippocampal* area (e.g., Staresina & Davachi, 2009), this is not observed for intrinsic binding processes (e.g., Parra et al., 2014).

To investigate this, we experimentally manipulated the type of binding required and observed the influence on three major phases of the WM task: during encoding, maintenance and target evaluation (see *Figure 27*). Further, we observed how electrophysiological signals as well as age-related changes to WM performance can substantiate these behavioral findings.

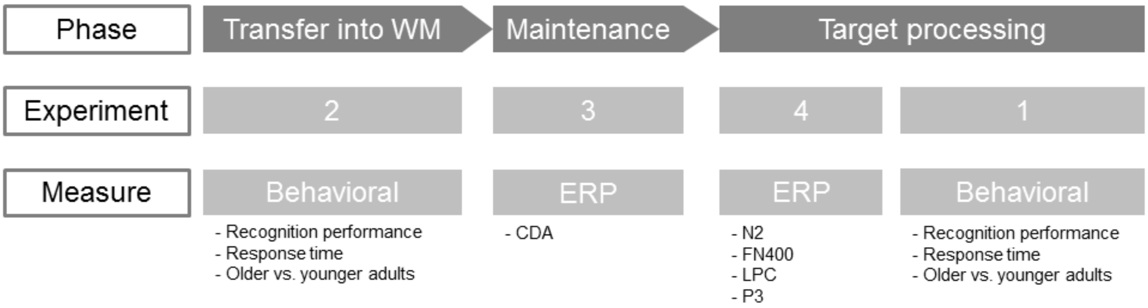

Figure 27: Temporal phases of the short-term retention of visual information as addressed in the current dissertation project.

Within the following sections, we will, first, give a short overview on the experiments conducted and the main findings. We will then carefully examine how the obtained findings fit the assumptions raised by the type-token model (Zimmer & Ecker, 2010). The results have implications for the generalizability of LTM binding mechanisms on the short-term retention of different object-feature associations. We will then argue that attention modulation processes are a key determinant for feature integration into object representations.

6.1 OVERVIEW OF THE EXPERIMENTS

In **Experiment 1**, we investigated whether storing intrinsic object-feature bindings is a rather cost-free process and extrinsic binding is more demanding. We hypothesized that *intrinsic* information is *automatically integrated* into a WM representation independent from task-demands, while binding of extrinsic features has to be intentionally engaged. This assumption was based on previous studies on LTM indicating that intrinsic but not extrinsic binding is related to rather automatic processes of familiarity, while extrinsic binding manipulations affected neurophysiological signals associated to rather conscious recollection processes (e.g., Ecker et al., 2007a, 2007b). In addition, it was examined, whether extrinsic binding in WM relies on intact hippocampal functioning to a greater extent than intrinsic binding (see Hannula & Ranganath, 2008). To this end, we focused on the comparison between a younger and an older sample, as the hippocampus is found to be one of the first areas to be affected by age-related deterioration (e.g., Raz et al., 2010). Change detection performance for shape-color bindings was tested under intentional and unintentional encoding conditions: A direct test demanded the participants to indicate whether a specific shape-color association changed from study to test. An indirect test investigated the obligatory nature of the integration of intrinsic and extrinsic color information into the WM representation. Other than expected, we observed no age-related association deficit-like memory impairment for extrinsic bindings if the stimulus was intentionally processed. However, older but not younger participants had a significant deficit in the processing of extrinsic bindings if the shape-color association was not intentionally heeded. Hence, we found strong indications that the distinction between intrinsic and extrinsic information is critical for WM performance, and processing of both stimulus types is differently affected by age-related degradation. However, older participants may be able to compensate for extrinsic binding deficits under intentional encoding conditions.

Experiment 2 was performed to investigate whether extrinsic binding can be understood as a *supplementary* process to intrinsic binding. If extrinsic binding associates two separate entities (or tokens) one would expect this process to be downstream to intrinsic binding (Cabeza, 2006; Delvenne & Bruyer, 2004). To this end, we investigated the encoding phase by gradually varying the exposure duration of intrinsic and extrinsic memoranda. As Experiment 1 yielded indications for age-related changes in extrinsic binding performance, we expected these decrements to be more pronounced if less time is available to compensate for (Rhodes et al., 2017). In addition to an overall lower WM performance, older adults showed significantly decreased WM performance for extrinsic shape-color associations. Other than expected, this effect was independent from the time available to encode the stimuli. Strikingly, the age-related binding deficit for extrinsic stimuli was most likely not a result of an impaired binding process but of a more general decrease in extrinsic features processing. Experiment 2 further corroborates the assumption that different binding mechanisms are not the underlying motors for processing differences between intrinsic and extrinsic stimuli.

In **Experiment 3** we, investigated the cognitive requirements during maintenance of both stimulus types. As extrinsic binding demands for the integration of separate visual entities, we hypothesized that ERPs associated to WM maintenance should vary if extrinsic object features are stored in an *higher-order representation* with increased storage demands (cf. Luria et al., 2010). In line with previous results, WM performance was poorer for extrinsic compared to intrinsic shape-color associations. However, behavioral effects at the time of test could not be attributed to different requirements during the maintenance phase, as reflected by electrophysiological signals related to storage demands. Instead, intrinsic and extrinsic stimuli can be maintained as integrated units in WM.

Experiment 4 substantiated that early attentional selection effects can track the processing differences between intrinsic and extrinsic information. We hypothesized that electrophysiological signals should vary with intrinsic object feature changes independent of task demands, if the processing advantage of intrinsic features is based on *involuntary* or obligatory availability of intrinsic but not extrinsic features. We used a two-fold design:

In a direct test, participants were required to store the shape-color associations and indicate changes to either shape or color feature changes. In an indirect test, shape information had to be monitored and the costs caused by changing irrelevant color information were measured. Under intentional encoding conditions, comparable electrophysiological signals associated to mismatch were found for intrinsic and extrinsic stimuli. If the association was not task-relevant, however, task-irrelevant changes for intrinsic but not extrinsic colors influenced early ERPs related to mismatch detection, as reflected by the N2. This provides a possible mechanism for the increased likelihood of intrinsic feature processing of intrinsic but not extrinsic information. Further, we found first indications that these early effects influence later more conscious processes of target evaluation, as reflected by P3-like positive component latencies. Findings suggest that feature integration is not obligatory under all conditions but influenced by task-related focus of attention.

6.2 HOW DO THE DATA FIT THE MODEL?

In the following sub-sections, we discuss the assumptions of the type-token model (Zimmer & Ecker, 2010) on the processing of intrinsic and extrinsic information against the obtained data on WM. We (1) highlight that intrinsic as well as extrinsic information can be retained as integrated objects. Although extrinsic information processing has to be intentionally engaged, our findings (2) suggest that extrinsic binding is not a supplementary process in terms of cascading mechanisms. We found constant processing differences for intrinsic and extrinsic object-feature associations. Most important, these were observed for bound and feature information, alike. The obtained results let us assume that (3) the influence of the visual distribution of features (intrinsic, extrinsic) is not restricted to binding mechanisms but influences WM functioning to a more general extent. The allocation of the attentional focus appears to critically influence the memory performance for intrinsic and extrinsic information in WM (for a comparable discussion, see Xu & Chun, 2007). Representations in WM can (4) be incomplete, with intrinsic features receiving an increased likelihood to be represented compared to extrinsic information. These observations (5) have implications on possible neurophysiological structures mediating the processing difference between intrinsic and extrinsic information processing.

6.2.1 IS EXTRINSIC INFORMATION MAINTAINED AS A HIGHER-ORDER REPRESENTATION?

Processing extrinsic object features requires the representation of disjunct features. Referring to LTM mechanisms (Zimmer & Ecker, 2010), we hypothesized that extrinsic feature associations can be intentionally integrated into a higher-order representation. However, if extrinsic object features should be represented as separate entities in WM, one would expect increased demands on the WM system (e.g., Luria et al., 2010). In Experiment 3, we chose the CDA as a neurophysiological correlate of the maintenance demands of represented units (Luria et al., 2016; Vogel & Machizawa, 2004) and the informational load of the memoranda (e.g., Gao et al., 2009; Gao et al., 2013; Luria et al., 2010) to track the differences in the ease of retaining intrinsic and extrinsic stimuli in WM.

On a behavioral level, Experiment 3 yielded two results. First, adding features to stimuli (i.e., adding a color to a monochrome stimulus) reduced WM performance and prolonged RTs. Second, WM performance was lower for extrinsic compared to intrinsic feature associations. Most important: electrophysiological slow waves did not vary according to behavioral performance. We observed highly similar CDAs across all conditions during the maintenance phase of the change detection task. With respect to our initial hypotheses, this ERP pattern has two implications. First, there were no indications that the CDA was sensitive to informational load. Potentials of the CDA were in a plausible amplitude range compared to previous studies (e.g., Gao et al., 2013; Ikkai et al., 2010; Luria et al., 2010) and thus let us assume that the present results indicate that the neurophysiological activity related to maintenance was not influenced by the number of features that were task-relevant. This was observed for intrinsic and extrinsic stimuli. However, results fit the assumptions of researchers referring to the CDA a strong correlate of object representation currently held in WM (Luria & Vogel, 2011; Quak et al., 2018; Vogel & Machizawa, 2004).

This leads to the second implication. Intrinsic and extrinsic feature associations do not diverge during maintenance. Considering the strong object position, this can be interpreted as intrinsic as well as extrinsic feature associations can both be represented as an integrated entity (e.g., Luck & Vogel, 1997). Other streams of research refer to the CDA as a correlate of the mental effort needed to retain information (Gao et al., 2013; Luria et al., 2010). According to this view, we can assume that the retention of intrinsic and extrinsic feature associations does not pose different demands on the maintenance process.

The observed memory performance differences between intrinsic and extrinsic stimuli are, thus, not the result of extrinsic feature associations placing an increased mental "burden" during retention. It is, however, important to note that this does not exclude the possibility that intrinsic and extrinsic feature processing do recruit different binding mechanisms when the visual percept is transferred into WM (Experiments 1 and 2).

Moreover, electrophysiological findings at the time of test suggest that intrinsic and extrinsic information can be accessed with different ease (Experiment 4). In the next section, we will, thus, argue that the extrinsic binding process during encoding of a stimulus into a WM representation is not downstream to intrinsic binding in terms of a temporal domain.

6.2.2 THE SUPPLEMENTARY NATURE OF EXTRINSIC BINDING

The association of extrinsic information is assumed to be a supplementary process to intrinsic binding, as disjunct units of information have to be integrated into a representation (Zimmer & Ecker, 2010). Data analyses to both Experiment 1 and Experiment 2 yielded that information about feature bindings was available to the participants. In both experiments, the observed WM performance during trials requiring knowledge about feature bindings (recombination trials) was significantly higher than what would be expected if independent features were stored. However, if extrinsic binding is a supplementary engaged to intrinsic binding, we would likely observe different encoding demands for intrinsic and extrinsic stimuli (Delvenne & Bruyer, 2004). Data of Experiment 2 does not speak for the transfer of visual information into a stable representation to develop faster for intrinsic bindings than for extrinsic. Both stimulus types showed almost identical performance gains with increasing exposure duration of the memoranda. Most important, this effect was found for feature *and* binding memory. *Supplementary* should therefore not be understood in a temporal domain as a slower or cascading process. However, as will be discussed below, it has to be intentionally engaged.

A constant advantage was observed for the intentional processing of intrinsic over extrinsic bindings across short (Experiment 2) and longer encoding times (Experiment 1). This effect was observed across younger and older age groups. Contrary to our expectations, this processing advantage for intrinsic over extrinsic stimuli was unlikely the result of prolonged time needed to transfer extrinsic bindings into WM. Both stimulus types profited to similar extents from increased exposure duration. Of particular interest is the finding, that recognition performances for the slowest-to-encode single feature (shape) and binding memory were not distinguishable at shorter stages of encoding (Experiment 2). This was observed for intrinsic and extrinsic stimuli. One explanation might be that both stimulus types do not require any binding process. Feature stores might be individually filled and features are retained individually in WM. Recognition performance is then reduced when multiple features have to be operated in parallel (e.g., Wheeler & Treisman, 2002). An alternative explanation is provided by object-based WM accounts that suggest that the visual WM operates with the integrated object. The slowest-to-encode feature limits this process (e.g., Luck & Vogel, 1997; Vogel et al., 2001). Similar to our findings from Experiment 2, these results have already been reported for the encoding rate of intrinsic stimuli (e.g., Woodman & Vogel, 2008). Both alternatives imply that the transfer of intrinsic and extrinsic information into WM can take place in a comparable manner provided that the information is intentionally encoded.

In contrast to the procedure utilized in Experiment 2, our stated goal in Experiment 1 was to minimize the influence of the time available to encode the information during the study phase. Nevertheless, we observed a memory benefit for intrinsic over extrinsic stimuli for bound and feature information if the shape-color association was intentionally encoded. Further, this effect remained stable across the lifespan. Such a remaining memory difference independent of time should not be likely if the transfer of different binding types from the percept into a stable WM representation takes place with different temporal structure. This supports the findings from Experiment 2 suggesting that the processing time is not a critical variable that differentiates intrinsic and extrinsic binding performance.

With respect to age-related changes in information processing, we found no indications that the influence of exposure duration to the memoranda for extrinsic bindings was differentially affected by age. Against the background of the deterioration of cognitive performance in old age (e.g., Chen & Naveh-Benjamin, 2012; Fandakova et al., 2014), we expected extrinsic binding to be especially slowed with increasing age (see Rhodes et al., 2017, for a similar discussion). Increasing exposure durations could allow the deployment of additional cognitive resources to safely store task-relevant information (Allen et al., 2006; Allen et al., 2012; Rhodes et al., 2016) – differences in the processing of intrinsic and extrinsic information should, therefore, become especially apparent if the exposure duration is short. We did not observe a time-dependent age-effect in WM performance. This supports the assumption that time available to encode the information is not a key determinant for the differentiation of intrinsic and extrinsic binding.

In sum and with respect to the temporal domain investigated in the present dissertation project, the time course of the encoding process for intrinsic and extrinsic information appeared to be of subordinate importance for the processing differences between intrinsic and extrinsic information. However, we do not exclude a “supplementary” nature of extrinsic feature processing in general: As discussed in the next section, the comparison between the intentional and unintentional processing of both stimulus types, as well as the analyses of ERPs involved in target processing, strongly suggest that extrinsic but not intrinsic features demand for a more deliberate engagement of attention.

6.2.3 INTENTIONAL VERSUS OBLIGATORY BINDING AND REPRESENTATION OF FEATURES

In the following, we will, first, argue that for WM, and in line with the assumptions raised by the type-token model (Zimmer & Ecker, 2010), intrinsic bindings are obligatorily processed. In contrast, we found clear indications that extrinsic binding has to be deliberately engaged. However, an intrinsic processing advantage is found for binding and feature memory suggesting that the binding mechanisms is not entirely responsible for the memory difference between intrinsic and extrinsic stimuli. We argue that the processing advantage of intrinsic over extrinsic stimuli is based on an increased likelihood of intrinsic feature information being available to target processing.

6.2.3.1 The Contribution of Binding to Intrinsic and Extrinsic Information Processing

Experiment 1 and Experiment 2 allowed the comparison of the recognition performance for new feature changes and recombination changes. In the former case, recognizing that a feature was not presented in the study array is theoretically suitable to indicate a "change". Thus, memory for isolated features is sufficient to solve the task correctly. In the latter case, features presented during the study array are recombined and (due to the central probe position utilized in Experiments 1 to 4) presented in a new location. Participants are thus required to evaluate whether this particular feature pairing was presented before, arguably providing a more strict test for binding information (Wheeler & Treisman, 2002). From the memory performance for new feature changes, a memory performance score can be estimated that represents a theoretical threshold for what memory performance would be expected from mere evaluation of multiple co-represented independent features. Comparisons between new feature and recombination changes can thus contribute to the investigation of represented bound information.

Overall, memory performance in the recombination condition was always better than what would be expected from the independence assumption (Experiment 1 and 2). This observation suggests that a limited WM resource is unlikely devoted to independent features; instead features profit from belonging to the same object as they were attended together, what appeared to increase the likelihood that features were co-represented. Since the detection of recombination changes was possible, information about bound object features could, in fact, be represented and supported recognition performance, which has been previously reported (e.g., Allen, 2015; Delvenne & Bruyer, 2004; Ecker et al., 2013; van Geldorp et al., 2015).

Moreover, we also observed higher recognition performance for intrinsic compared to extrinsic stimulus bindings if participants were required to intentionally store them (for comparable results, see, e.g., Delvenne & Bruyer, 2004; Ecker et al., 2013; van Geldorp et al., 2015; Walker & Cuthbert, 1998). Strikingly, this processing benefit for intrinsic feature associations was not only found for binding memory (as in Experiments 1 and 2); it was also observed for memory for single features (Experiments 1 to 4). Apparently, the visual format does not only influence necessary binding processes but is also central to stimulus feature processing in general.

This has two major implications. First, the processing benefit of intrinsic bound information is *unlikely* the result of a more demanding extrinsic *binding* process. Instead, our data strongly suggest that extrinsic feature binding has to be *intentionally* engaged, while intrinsic feature bindings are almost unintentionally provided to WM. This argumentation is based on the observation that we did not find an age-related binding deficit for extrinsic stimuli if intentionally heeded (Experiment 1 and 2). However, older adults yielded pronounced performance costs caused by task-irrelevant intrinsic feature changes, and these were in stark contrast to almost absent costs for task-irrelevant extrinsic new-feature and recombination changes. This difference is all the more surprising, as a large body of work suggests that cognitive inhibitory processes should decrease with age (for an overview, see for example Hasher, Zacks, & May, 1999). As a consequence, older adults are expected to be less able to inhibit task-irrelevant information during WM tasks (Jost et al., 2011; Schwarzkopp, Mayr, & Jost, 2016). Our results from Experiment 1 indicate that this is true for intrinsic but not extrinsic stimuli: RT costs associated with the response conflict arising from irrelevant intrinsic feature changes were approximately twice as large in older compared to younger participants. Importantly, older participants showed comparable costs for recombined and new feature changes. Hence, slower responses were not an unspecific interference effect but a consequence of remembering the “correct” (i.e., studied) color. This suggests that in intrinsic stimuli, color was in fact bound to shape even though it was not task-relevant. In other words, a recombination of old features could only create conflict if the studied shape-color association is represented in memory. Thus, the larger costs for older participants are consistent with previous findings of greater age-related costs associated with the filtering out of irrelevant information (Gazzaley, Cooney, Rissman, & D'Esposito, 2005; Hasher, Quig, & May, 1997; Jost et al., 2011; Oberauer, 2005). The lack of interference from task-irrelevant extrinsic features is, therefore, unlikely the result of older adults being able to inhibit the information. Instead, processing of extrinsic bindings is more susceptible to age-related deteriorative processes while processing of intrinsic information is largely preserved.

Most important, however, no extrinsic binding deficit was observed if older adults were required to intentionally store the shape-color associations. This observation should not be possible, if the representation of associated feature bindings is provided via dedicated binding mechanisms that is impaired due to age-related deterioration (Raz et al., 2010). Instead, we observed that older adults were able to compensate the extrinsic binding deficit if the association was intentionally heeded. Directing attention toward the association of features or not (direct vs. indirect test condition) thus critically influenced intrinsic and extrinsic stimulus processing. Hence, the process of modulating the focus of attention appears to be a key determinant in the mediation of binding information.

Second, the memory benefit for intrinsic stimuli is not restricted to bound stimulus information. Instead, we consistently observed an increased probability for intrinsic information to be represented in WM compared in general compared to extrinsic information. This is supported by older adults' decreased ability to process task-irrelevant extrinsic bound as well as feature information independent from the time available encode the information. In Experiment 1, encoding times were estimated to minimize effects related to perceptual processing; the missing interference for extrinsic feature changes is, hence, most likely not the result of an age-related impairment related to perceptual deficits. The effect of the time available to consolidate the information was, however, tackled in Experiment 2. There, however, intrinsic and extrinsic feature processing did not differentially profit from increasing the time available as soon as sufficient perceptual encoding was enabled[8], neither for younger nor older participants. From the time range investigated in our Experiments 1 and 2, we found no indications that an increase in the exposure duration differentially influenced how older and younger participants process intrinsic and extrinsic feature bindings. What remained as a driving factor distinguishing both stimulus types was a decreasing likelihood for extrinsic features to be represented in WM; an effect that became more pronounced as age increased.

One potential mechanism for a reduced likelihood for extrinsic information to reach WM could be that extrinsic feature processing demands for a more flexible allocation of attention across the stimulus area. A recent study from Weeks and Hasher (2018) indicates that the ability to focus the scope of attention on the areas essential to the task diminishes with age. In a priming experiment, the authors showed that younger subjects were better able to focus on a single image and inhibit the influence of a superimposed word than older subjects. Similarly, Greenwood and Parasuraman (2004) found, that older adults were less able to use cues to appropriately scale their focus of attention to task

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[8] Please note that Naveh-Benjamin and Kilb (2014) found that mechanisms related to sensory decline can influence the processing of associative information in WM.

demands in a visual search task. In line with this, findings from Experiment 2 yielded an overall reduced probability for extrinsic information to be transferred to WM arising with age, even under intentional encoding conditions. In line with these findings, we observed older adults to be less able to process extrinsic information if not intentionally heeded (Experiment 1, indirect test) but being able to compensate for this when given enough time to process the information after the task was cued (Experiment 1, direct test). However, if no sufficient time was given, older adults could be less able to fully compensate a reduced ability to flexibly adapt the focus of attention to the extrinsic information[9] (Experiment 2). This could have led to the observed reduced processing of extrinsic features in general.

In sum, the observed processing differences between intrinsic and extrinsic feature processing and binding performance put weight on the assumption that the driving mechanism is unlikely grounded in the consolidation process but rather based on differences in earlier processing demands of both stimulus types. The formation of extrinsic bindings requires a more superordinate controlled process that relies on an intentional engagement. Hence, the *binding process* per se is unlikely the major determinant driving the processing advantage of intrinsic over extrinsic stimuli but *modulating the focus of attention* could significantly contribute to differences in intrinsic and extrinsic feature processing in general. In the following section, we will discuss electrophysiological data that provides strong indications for intrinsic but not extrinsic information passing early attentional selection processes and thus contribute to target processing.

6.2.3.2 The Obligatory Representation of Intrinsic but not Extrinsic Features

As reported above, we observed an increased likelihood for intrinsic features to be represented in WM compared to extrinsic. This observation fits the framework of the type-token model (Zimmer & Ecker, 2010). Most important, electrophysiological observations from Experiment 4 strongly suggest that intrinsic information is *obligatorily* represented in WM.

Under intentional encoding conditions (direct test, Experiment 4), changes to intrinsic as well as extrinsic features elicited comparable mismatch signals, as found in the N2 and FN400-like ERPs. This indicates that in WM both stimulus types are in fact capable of influencing early processes involved in target processing (Wang et al., 2004). Different findings were obtained under unintentional encoding conditions (indirect test): For intrinsic stimuli, task-irrelevant color feature changes elicited early ERP signals of

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[9] Please note that the upcoming stimulus type was not known to the participant.

mismatch detection in the time window of the N2 and the FN400. By contrast, for extrinsic stimuli, ERPs elicited during task-irrelevant color change conditions followed the form of no-change conditions. With respect to the FN400-like component, this result is similar to previous findings from LTM, suggesting that components related to familiarity are engaged for intrinsic but not extrinsic feature associations (Ecker et al., 2007a, 2007b). With respect to the N2, the finding is at odds with a number of studies showing that irrelevant changes to color in general can elicit an early mismatch effect (Folstein & van Petten, 2008; Gao et al., 2010; Wang et al., 2004; Yin et al., 2011; Zhou et al., 2011). The observed ERP pattern thus suggests that intrinsic information is an obligatory part of the representation used to evaluate the test probe. Extrinsic information, by contrast, is only involved in early processes of target evaluation if intentionally heeded. Our data observed in Experiment 4 thus highlights the importance of early target processing for the distinction between intrinsic and extrinsic stimulus types.

We suggest that the obligatory availability of intrinsic feature information is a central mechanism for the processing advantage of intrinsic over extrinsic stimuli: Subgroup comparisons from Experiment 4 yielded first indications that the availability of additional (intrinsic) feature information could influence later components in the time window of the P3. Positive components in this later time window are often assumed to reflect the decision to an adequate response, with the initiation being represented as the peak latency of the wave (Kok, 2001; Polich, 2007; Verleger, Jaśkowski, & Wascher, 2005). In Experiment 4, we observed that an increased early mismatch signal in the time window of the N2 associated with task-irrelevant information can lead to an *earlier* peak of the later P3-like positive component. This was surprising, as we would have rather expected decision making process to be "delayed" if interference has to be resolved. ERP data suggests that as soon as an object is attended, object-inherent intrinsic information experiences some form of attention alongside the shape. The same appears not to be true for extrinsic object information that is disjunct from the shape, as no corresponding pattern was observed for task-irrelevant extrinsic feature changes. As the P3-like positive component was found to be related to change evaluation in Experiment 4, we suggest that part of the processing advantage of intrinsic over extrinsic stimuli could be that the decision making process during target evaluation can profit from the (increased) availability of intrinsic information. We therefore argue that early signals of mismatch detection can support some form of cognitive control system that is needed to proper solve a mental task, as suggested by Cavanagh and Frank (2014). However, these effects were not visible in terms of behavioral response timing. Clearly, further research is needed to corroborate these findings and evaluate the obligatory role of intrinsic information.

With respect to our initial assumptions within the framework of the type-token model (Zimmer & Ecker, 2010), electrophysiological data on early processes of target processing clearly show an influence of intrinsic but not extrinsic feature information irrespective of task-demands. In contrast to extrinsic object features, intrinsic information is found to be *obligatorily* represented in the WM template used to evaluate the target. The early availability of intrinsic object information appears to contribute to later processes associated to decision making, what can potentially improve WM functioning. Our findings have implications on the discussion about "what" is represented in visual WM, as will be reported in the next section.

6.2.4 IMPLICATIONS ON OBJECT REPRESENTATION

In Chapter 1.3, we discussed different models of how information is represented in WM. The strong object-based approach assumes that the visual WM operates with integrated objects in an "all-or-none" manner (e.g., Luck & Vogel, 1997; Vogel et al., 2001), that is an object and its features are either completely represented or can be completely lost. Feature-based models assume that representing information in visual WM is influenced by the number of features per object (e.g., Oberauer & Eichenberger, 2013). Findings from the present dissertation project contradict purely object-based representations to serve a WM task. However, models suggesting independent storage of features cannot explain the obtained data in total. Findings from the present thesis fit best models that allow for the incomplete representation of objects, such as provided by Cowan and colleagues (2013).

Electrophysiological measures argued to reflect storage demands during the retention interval (e.g., Luria et al., 2016) suggested that intrinsic and extrinsic stimuli did not differ in terms of representational format or mental effort needed to maintain the representation (Experiment 3). In line with object-based models of WM representations, the CDA did not differ between conditions where the complete object or only single features of the objects were relevant; instead, as always two objects were presented, the CDA was constant across conditions. ERPs related to early mismatch detection were influenced by intrinsic feature changes irrespective of task-demands suggesting that intrinsic feature were always part of the WM representation; this supports object-based models as they would expect that objects are always represented in their entirety. Further, if encoding times were short, participants were to a certain extent able to process object features in parallel (Experiment 2). These observations are in line with the assumption that the visual WM operates with integrated objects.

However, we found that the slowest-to-encode object feature moderated the integration of information into a WM representation (Experiment 2). Especially under condition with restrained time to encode the information into WM, binding performance was on a similar level as memory for (the slowest-to-encode) features. Such an influence has been reported previously (e.g., Woodman & Vogel, 2008). This finding contradicts a strong object-based information processing but suggests that features are to some extent independently processed, for example as suggested by models that assume that the visual WM operates in a coarse-to-fine manner, enriching easy to encode feature information with incrementally with more complex information (e.g., Gao et al., 2013). In line with this, we repeatedly observed that recognition performance was better for color compared to shape features (Experiment 1 and 2). However, memory for features but not memory for bound information profited from increased encoding times (Experiment 2). Thus, the slowest-to-encode feature was not always represented with the easier-to-encode feature; this contradicts an object-based WM progression from coarse to fine features (Gao et al., 2013).

The findings on the processing of different stimulus types further stresses that no strong object-based WM representational mechanisms was observed in the research design; instead, we observed that objects features can encounter different fates in WM, following models of feature-based WM representation (e.g., Wheeler & Treisman, 2002). It could be shown that age-related changes to WM performance affected the involuntary processing of intrinsic and extrinsic shape-color associations differently (Experiment 1). We observed that intrinsic but not extrinsic feature information influenced early processes of target evaluation (Experiment 4). Furthermore, memory performance for intentionally encoded object-feature associations never fell beneath the threshold that would be expected if representing objects with multiple features is "*nothing more than independent attributes that are retained for the same object by chance*" (Cowan et al., 2013, p. 733; see also Vul & Rich, 2010). These findings support models of WM suggesting that the individual feature is the handled unit.

However, models of independent feature stores (e.g., Wheeler & Treisman, 2002) can also not account for all data. A considerable beneficial effect of binding information was observed in Experiments 1 and 2. Both Experiments allowed to test feature and binding memory separately and, thus, to evaluate the independent nature of the features. Findings from task-irrelevant recombination changes corroborated the interpretation that some information about feature bindings was available (Experiments 1 and 2). Binding thus contributed to WM performance, as memory for associations was significantly better than what would be expected if individual features were stored.

Our data might be best described by a WM model that represents multi-featured objects within some form of object file (Kahneman et al., 1992), but these representations can be incomplete: Whereas at least one feature is securely represented in an object file, the probability that additional features are added is smaller than 1 (Cowan et al., 2013). Features might initially be transferred into WM independently, but are then passed into a corresponding object feature co-representation. Experiment 1 and 2 yielded results that information about bindings between independent features was represented (recombined condition). Critically, the pattern of how the information is distributed across an object influences the likelihood with which a feature is transferred to WM in the first place (Experiment 4); however, our data suggests that this process appears to be influenced by task demands (direct vs. indirect test conditions). Depending on the currently active task set of the participant, attentional modulation can influence whether independent features experience an increased likelihood to be co-represented in some form of common object file.

According to the data of this research project, features that are perceived as intrinsic to an initial anchor are more likely to be integrated than extrinsic features. Support for the role of some form of representational anchor can be found in the ERP data during the intentional storage of shape-color associations. Changes to both shape and color features elicited early signals of mismatch[10] that were observed independent from stimulus type. In general, this finding replicates previous studies with single (e.g., Wang et al., 2004) and multiple memoranda in a WM task (e.g., Yin et al., 2012). In Experiment 4, however, we observed that shape changes elicited an enhanced N2 mismatch effect compared to color changes, what was not observed before (e.g., Gao et al., 2010, Experiment 4; Yin et al., 2012). Other than previous studies, we used a central probe throughout all experiments. This test format could have influenced the evaluation procedure needed to solve the task. In our designs, participants could not rely on location information but instead had to compare the probe to each studied representation (Cowan et al., 2013). But how could this have influenced the mismatch process?

Such a pattern of an increased mismatch signal for specific types of information has been observed in studies investigating neural resource consumption as indexed by increased cerebral blood flow: Studies on positron emission tomography in humans found that cognitive control processes modulating the focus of attention influence the cerebral blood flow. The control processes depend on the feature participants were to inspect (e.g., Corbetta et al., 1990, 1991). For the given Experiment 4, these findings indicate that the

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[10] Please note, that a N2 related to mismatch was also observed in Experiment 3. The corresponding analyses can be found in Appendix 3.

shape information produced an enhanced mismatch signal than the color information at test. This is contrary to previous theories of object-representation suggesting that simple features are the initials of representations. For example, Alvarez and Cavanagh (2008) argued that object features of different complexity are processed at different stages. Simple features with low-resolution information are extracted at an earlier stage and form initial proto-objects for representations. More complex information is added to the object in further steps; a comparable model was proposed by Gao et al. (2013). However, location information was not appropriate in the central probe paradigm utilized in the present dissertation project. As shape information was always task-relevant, the more complex shape information (see Experiment 2, where shape was the slower-to-encode feature) could have served as an "anchor" for the subsequent addition of color information (see Cowan et al., 2013, or Hyun et al., 2009, for a more in-depth discussion on the role of the test probe).

What defines the anchor for the representation thus might depend on task demands: earlier studies suggest that simple features such as colors are early components of the representation (Gao et al., 2013). This might be restricted to conditions when information can be bound to location. If location is not a sufficient component for the task, even more complex features (shape) could serve as the proto-object to form the WM representation which is then incrementally enriched with information (Gao et al., 2011). Most important, ERPs related to mismatch detection from Experiment 4 yielded only intrinsic information to influence early target evaluation process independent from task-demands. As intrinsic information is an inherent part of the shape anchor it is more likely to be transferred into a WM representation, as soon as the shape is attended. As a consequence, intrinsic feature associations are more likely to be created than extrinsic stimulus representations. However, it is important to note that our design yielded no clear results on later ERPs related to conscious retrieval processes (e.g., LPC, Experiment 4). Moreover, we never tested the recognition and/or retrieval of another feature explicitly, once one feature was recognized (see Ecker et al., 2013, Experiment 3). Clearly, further research is needed to investigate the role of more conscious stages of intrinsic and extrinsic stimulus processing.

In sum, we suggest the data obtained in the present dissertation project is be best explained by a WM system can co-represent independent features in a bound object file, but these object files can remain incomplete. Features inherent to an initial representational anchor are more likely to be integrated into the common object file and available at early stages of target processing, highlighting the importance of the visual pattern of how features are distributed across the memoranda. However, the transfer and integration process can be influenced by task-demands guiding attention. We argue that representing objects with multiple features *is* in fact *more* than "*independent attributes that are retained for the same object by chance*" (see Cowan et al., 2013, p. 733).

6.2.5 THE ROLE OF THE HIPPOCAMPUS IN VISUAL WM

Following the framework of the type-token model (Zimmer & Ecker, 2010) as well as neurophysiological models of WM (Konkel & Cohen, 2009; Yonelinas, 2013), we assumed that intact hippocampal functioning is of major importance for extrinsic feature binding in LTM and WM (for experimental results that emphasize the role of the Hippocampus in WM see, e.g., Piekema et al., 2009). The hippocampus is prone to age-related structural changes that are found to influence sound functioning (Fjell & Walhovd, 2010; Raz et al., 2005; Raz et al., 2010; Shing et al., 2010; Yang et al., 2013). Therefore, different age groups were investigated to contribute to our understanding of the role of intact hippocampal functioning for extrinsic binding processes in WM.

6.2.5.1 The Role of the Hippocampus for Extrinsic Binding in WM

If feature associations were intentionally heeded, we found no indications for qualitative age-related changes to extrinsic compared to intrinsic binding performance (Experiment 1, direct test, and Experiment 2). Instead, findings from Experiment 2 suggested a more general decrease in extrinsic feature processing arising with age. As a consequence, the evaluation of a test probe that demands for bound information (i.e., detection of a recombination change) is rather affected by a lack of information, than an impaired binding process due to age-related changes in hippocampal functioning.

This interpretation is supported by the comparison of the intentional and unintentional processing of extrinsic shape-color associations. Task-demands influenced the extent to which age-related binding deficits could be observed: while we observed a strong age-related binding deficit for extrinsic stimuli when the shape-color association was not intentionally heeded (indirect test, Experiment 1), no comparable extrinsic binding deficit was observed older adults when attention was intentionally directed toward the association (direct test, Experiment 1 and 2). Since we have no functional imaging data available, strong neuroanatomical claims are not possible at this stage. We might, however, speculate that older adults were able to compensate for an association deficit when attention was directed toward the shape-color combination.

One possible explanation for such compensation involves the adjuvant recruitment of more distributed processing network in old age (e.g., Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2010; Schneider-Garces et al., 2010). Recent neuroimaging studies indicate that older adults rely on a more bilateral neural activation (e.g., Vermeij, van Beek, Olde Rikkert, Claassen, & Kessels, 2012) or a more distributed and less-specialized recruitment of neural structures (e.g., Payer et al., 2006) when performing a similar task as younger adults. Indeed, brain imaging studies investigating the short-term retention of different types of information emphasize that activity in multiple brain regions contributes to WM performance, including parietal, inferior temporal, and prefrontal cortex areas (e.g., Ranganath, 2006; Ungerleider, Courtney, & Haxby, 1998).

Although we do not want to exclude the influence of intact hippocampal functioning on WM performance, the consequences of age-related hippocampal changes may only become visible under certain conditions. For example, Bergmann, Rijpkema, Fernández, and Kessels (2012) were able to show that activity in visuo-perceptual areas during the encoding of information was related to performance in WM tasks, whereas activity of the hippocampus during the encoding was mainly related to performance in a later LTM recognition task. In addition, neuropsychological data from Baddeley and colleagues supports the interpretation that complex binding tasks can be solved in spite of impaired hippocampal function: The authors (Allen, Vargha-Khadem, & Baddeley, 2014; Baddeley et al., 2010) investigated patient Jon, who suffered from highly selective hippocampal damage due to postnatal hypoxic-ischemic injury. Despite significant LTM deficits, Jon achieved high levels of WM performance across different binding conditions. These results corroborate the assumption that intact extrinsic binding performance is not solely hippocampus-dependent in WM.

In sum, we suggest, that age-related changes to hippocampal functioning did only to a minor extent influence extrinsic binding in WM; alternatively, older adults were able to compensate for this impairment. It appears likely that the reduced performance in extrinsic binding arising with age is the result of an overall reduced ability to adapt to extrinsic content.

6.2.5.2 Alternative Binding Mechanisms

How is bound information provided? Data of the current dissertation project fit best the assumption that we do not necessarily have to consider a dedicated neural structure such as the hippocampus when processing (extrinsic) shape-color associations in WM. Comparable to previous work (e.g., van Geldorp et al., 2015), we found no clear evidence that older adults reduced performance for extrinsic stimuli was based on a reduced binding ability. Instead, allocation of attention to the stimulus features (see Experiment 1) influenced memory for features and bindings. Moreover, Experiment 2 revealed a significant contribution of mere availability of extrinsic feature information to WM and binding performance. In addition, also younger adults were differently affected by task-irrelevant extrinsic feature changes depending on task-demands: When encoding time was short (Experiment 4, indirect test), younger adults were significantly more impaired by intrinsic compared to extrinsic task-irrelevant color changes, but these impairments were similar when encoding time was longer (Experiment 1, indirect test). Assuming intact hippocampal functioning in the younger sample, this pattern of results suggests that also younger adults were able to modulate processing of extrinsic features. However, as indexed by participants' performance in recombined conditions and location-independent probes, the information about which color is assigned to which shape must be represented in some way.

An alternative explanation that does not rely on a neural structure to provide a specific binding mechanism (e.g., Cer & O'Reilly, 2006) includes the firing rates of excited neurons: Such models suggest that binding can be achieved by coactivation of neurons involved in task-processing. If an information is processed, neurons in a common cell assembly related to processing fire simultaneously. Coactive neurons excite or reinforce each other's active status, a process also referred to as reverberation (for an overview, see Murre, Wolters, & Raffone, 2006). Indeed, such persistent firing related to the representation of no longer available sensory stimulation has been observed in cells of the primate dorsolateral prefrontal cortex (Wang et al., 2013).

A drawback of this concept is that coactivation cannot easily explain how multiple objects are segregated during retention. Critically, segregation was required in all experiments of this dissertation project, especially during paradigms that required the detection of a recombination change. Multiple-item short-term retention might be facilitated by synchronous spiking times of neurons coding the features of the same objects and their desynchronization with spiking times of other neurons. As pointed out by Engel, König, Kreiter, Schillen, and Singer (1992): "*perceptual coherence of features in a visual scene is reflected by synchronous firing of the corresponding feature-detecting neurons. Thus, neurons responding to features of the same object discharge in synchrony, whereas cells responding to different objects are assumed to fire in an uncorrelated manner*" (p. 220). According to this model, feature bindings can be maintained by correlated synchronized firing rates of task-related neurons. It is important to note that this interpretation already implies the existence of two different binding mechanisms (reverberation and synchronized firing).

Indeed, it is reasonable to assume that multiple binding mechanisms exist, operating at different task demands or representational formats. For example, Rainer, Asaad, and

Miller (1998) could show that the firing rate of neurons in the prefrontal cortex of monkeys was only related to task-relevant information of a sequential matching task, whereas task-irrelevant information did not affected the firing rate. This finding can be interpreted as controlled influence of prefrontal neurons on binding performance with information selection and maintenance (Murre et al., 2006).

We, thus, suggest that the tasks utilized to provoke extrinsic and intrinsic binding (Experiments 1 and 2) in the present dissertation project might not as heavily involve (intact) hippocampal functioning as observed for other forms of binding, such as object-location binding (e.g., Mitchell, Johnson, Raye, & D'Esposito, 2000). Especially the ability of older adults to compensate for extrinsic processing deficits (Experiment 1), as well as younger participants extrinsic feature processing dependence on task demands (compare indirect test performance in Experiment 1 and Experiment 4), let us suggest that binding information could have been provided without a dedicated neural structure or at multiple levels. Possible mechanisms include reverberation and synchronized firing in a distributed neuronal network (Zimmer, 2008).

6.2.6 COMPARISON OF THE LTM MODEL AND WM FINDINGS

To sum up, the distinction of intrinsic and extrinsic stimuli can significantly contribute to our understanding of WM functioning. However, it became apparent that the assumptions of the type-token model (Zimmer & Ecker, 2010) from LTM cannot be adopted in all parts for WM. We found no indications that intrinsic and extrinsic stimuli are maintained in different representations or that the maintenance demands differ between both stimulus types. However, our findings strongly suggest that intrinsic but not extrinsic information is obligatorily integrated into a WM representation, while the transfer of extrinsic information demands for a more intentional command; however, we found no indication that this happens in form of subsequent or cascading processes. Most important, the processing advantage of intrinsic over extrinsic stimuli is not driven by differences in the binding process but more likely by the increased likelihood of intrinsic features being transferred to and accessed in WM. Intrinsic but not extrinsic information can thus support early mechanisms of target evaluation in a WM task. Age-related changes to neurophysiological functioning did influence WM performance in general, but did not lead to the expected extrinsic binding decrements. Instead, older adults appeared to be able to compensate for a processing deficit for extrinsic features in general. In contrast to LTM and together with findings from the comparison between the intentional and unintentional processing of both stimulus types, a dedicated binding structure, such as the hippocampus, might not be mandatory extrinsic binding in WM. Instead information about feature bindings in WM appears to be provided via the joint encoding of attended features. In the following section, we will therefore discuss the importance of attention for the processing of intrinsic and extrinsic information.

6.3 THE RELEVANCE OF ATTENTION FOR A PROCESSING BENEFIT

It remains an open question what drives the obligatory nature of intrinsic feature processing and the more deliberate processing of extrinsic features. In the following, we argue that attentional scaling could provide one key mechanism.

Attention might function as glue to retain bound features. The role of attentional processes is emphasized by the memory performance differences for intentionally and unintentionally processed extrinsic features (Experiments 1 and 4). O'Craven et al. (1999) suggested that intrinsic binding operates automatically if an attended object can be separated as a distinct entity from the ground. From our data, we suggest that *attending* an object is not a unitary process. The pattern with which task-relevant or task–irrelevant visual information is presented across an object (see also Fougnie et al., 2010) not only influences where the observer has to shift his or her attention, it also influences the spatial scope of the focus of attention.

6.3.1 SPATIAL ATTENTION

Here, we refer to attention as the "*malleable, movable resource that can heighten processing within regions of space where it is di-rected* [*sic*]" (Greenwood & Parasuraman, 2004, p. 3). This covers three important aspects for the processing of different stimulus types: first, the attentional resource can be moved, often also referred to as *shifting* attention between multiple spots of interest, voluntarily or involuntarily (Chun, Golomb, & Turk-Browne, 2011). Second, the spot of attention is malleable, which implies that the focus can be *scaled* dynamically (Eriksen & St. James, 1986). And third, dimensions within the scope of attention are heightened, that is attended feature dimensions can be given an increased *weighting* for cognitive processing thereby biasing the perceptual system toward the processing of this dimension while inhibiting others (e.g., Müller et al., 2003). If attention is focused to a circumscribed small area, a higher density of attentional resources is available to the information in this spot (Heitz & Engle, 2007). Depending on the attentional resources, intrinsic and extrinsic features could thus experience different processing gains.

With respect to the data of the present dissertation project, as soon as the shape information is attended, the intrinsic color is likely to become an integral part of the attended shape. That is, the shape of the object defines the primary outline of the *attended* area, since shape was important in indirect and direct WM tasks, alike. As the intrinsic color itself shares the outline with the shape, color could be manipulated independently from the shape but it cannot be attended independently from the shape. In contrast, the extrinsic frame can be separated from the shape. Extrinsic color information, if not intentionally heeded, does not experience the same form of processing gain as the shape information. The focus of attention has to be adjusted to cover the extrinsic information. Therefore, the scaling of the attentional scope might have significantly impacted the differential processing performance of intrinsic and extrinsic features.

6.3.2 THE RELEVANCE OF ATTENTIONAL SCALING FOR INTRINSIC AND EXTRINSIC INFORMATION PROCESSING

The distribution of color information operationalized for intrinsic and extrinsic stimuli in the present series of experiments varied in spatial distribution. Critically, attentional scaling is found to be influenced by time, as provided by findings from Greenwood and Parasuraman (1999). In a visual search task, participants were required to indicate the presence or absence of a target letter (e.g., a pink T) among a group of colored letters. A location precue presented 500 ms before the search array improved search times. Critically, this beneficial effect significantly decreased when the precue interval was shortened to 200 ms (comparable results on the time course of cue effects where found, e.g., by Müller & Rabbitt, 1989). Moreover, Heitz and Engle (2007) found that participants with higher WM capacity were able to scale their attentional zoom lens faster, resulting in an earlier decrease of distractor-related impairments. These findings suggest that scaling the scope of attention influences performance in visual tasks.

Hence, the ability to scale the focus of attention could have been of critical importance for the processing of task-relevant and task-irrelevant intrinsic and extrinsic information. As soon as the attention is focused on a shape, the intrinsic color experiences a processing gain, transferring it into a state of increased accessibility (Cowan, 1988, 1995). However, an adaptation of the focus of attention over a larger area is necessary for the processing of extrinsic information. As a consequence, less attentional resources are now available for each unit of area (for a similar discussion, see Heitz & Engle, 2007, p. 219). Conversely, the increased scaling demands of extrinsic information lead to decreased influence of task-*irrelevant* extrinsic information on WM performance (see, e.g., N2 and P3-like components in Experiment 4).

The randomized stimulus type presentation used in all experiments of this dissertation project made the constant re-scaling of the attentional focus necessary. During the intentional encoding trials of the direct test, participants could rely on the cue indicating that both features are relevant to the task and prepare the scaling process, potentially with the task-set of “extrinsic” as some form of default to not miss potential extrinsic feature information. In the shape-only indirect task, it could have been beneficial to set the attentional scaling default to “shape”. Indeed, this was reported by some participants in a post-experiment questionnaire from Experiment 1. Future research could reveal that the processing advantage for intrinsic over extrinsic information is attenuated if the stimulus type presentation is blocked; that is, participants can adapt to a consecutive presentation of only intrinsic or extrinsic stimuli.

At this point it is important to discuss why we observed that younger adults were equally hampered by task-irrelevant changes to intrinsic and extrinsic information in Experiment 1? In 2010, Gao and colleagues argued that basic or highly-discriminable features are automatically integrated in WM representations, whereas more complicated features are neglected if not relevant to the task (see also Gao et al., 2011). As assumed by the type-token model, extrinsic information is not extracted at parallel stages – instead, integration of extrinsic information is argued to be rather deliberate (Ecker et al., 2013). Why did we find a significant influence of extrinsic information? One potential reason might be that we used encoding times that largely exceeded those from Gao and colleagues (2010). In our Experiment 1, we individually estimated the time needed to ensure sufficient time to encoding the information. Thus, in our study, the missing difference between intrinsic and extrinsic distraction effects in younger adults could be the result of a top-down controlled compensation for increased processing demands of extrinsic stimuli. In line with this interpretation, we did find differential distraction effects in Experiment 4, where we used an encoding time of 200 ms, similar to Gao et al. (2010). With significantly shorter exposure duration of the memoranda, the attentional scaling process was challenged even for younger adults. This distinction further corroborates the assumption that intrinsic and extrinsic information differ in their demands on a top-down modulated availability of some form of attentional resources.

Findings from Experiment 4 might fit the assumption that intrinsic information poses lower demands on attentional scaling processes compared to extrinsic information: on trials correctly solved by the participant (i.e., task-irrelevant changes to features did not lead to an erroneous response), intrinsic but not extrinsic feature task-irrelevant feature changes elicited an early N2 mismatch signal, while the signal associated with task-irrelevant extrinsic feature changes was not distinguishable from a “no change” trial. Moreover, as alluded to earlier, these early N2 mismatch effects influenced the latencies of later P3-like positive components (Kok, 2001). This could indicate that a classification of the intrinsic stimulus was possible within a shorter range of time. Here, we are in line with the assumptions from Ecker et al. (2013) about intrinsic features in WM: findings from the present research project put weight on the interpretation that intrinsic information, as opposed to extrinsic information, is obligatorily processed. Our electrophysiological findings corroborate the assumption that the intrinsic processing advantage is indeed based on earlier rather perceptual mechanisms related to the need for attentional scaling, which we found to be more demanding for extrinsic information.

WM is, thus, not an isolated process but appears to operate in close interaction with perception. This position was put forward, for example, by Gao and colleagues (2011). In a series of experiments, the authors provided compelling evidence for an interactive model of perception and WM. The authors suggest that the visual WM does not operate with final entities of percepts. Instead, "*how information is extracted during visual perception will directly impact how the information is going to be selected*" (Gao et al., 2011, p. 1821).

6.3.3 AGE-RELATED CHANGES TO ATTENTIONAL SCALING

Previous research from visual search paradigms indicates that older adults show substantial decreases in the ability to scale the attentional gradient (e.g., Greenwood & Parasuraman, 1999, 2004; Lawrence, Edwards, & Goodhew, 2018; but see, e.g., Hartley & Kieley, 1995). Concurrently, however, the ability to use cues to guide behavior in a task appears to be largely preserved in old age. Older adults are found to benefit from cues to similar extent as younger adults (e.g., Souza, 2016). Thus, the impaired processing of task-*irrelevant* extrinsic information (Experiment 1, indirect test) but preserved processing of task-*relevant* extrinsic information (Experiment 1, direct test) in older adults could be the result of a decreased ability to flexibly scale the focus of attention if no valid cue precedes the trial. In the direct test, older adults could use the cue to prepare for intrinsic as well as extrinsic stimuli, since in any case shape and color information was necessary to solve the task. In the indirect test, however, the cue indicated that only the shape information was necessary, leading to an attentional scaling set to the level of the shape. However, it was unknown which stimulus type was presented. While younger adults were able to adapt to this if sufficient time was available, this ability was reduced in older adults. Put differently, older adults profited from the reduced ability to flexibly scale the focus of attention since less task-irrelevant extrinsic information was processed. The potential role of attentional scaling is further stressed by findings from Experiment 2, where older adults yielded a general decrease in extrinsic feature processing when encoding demands were increased: Since the encoding time was comparatively short in Experiment 2, it is possible that older adults were less able to compensate for slower scaling processes even in intentional processing condition (for a similar discussion, see Rhodes et al., 2016; Rhodes et al., 2017). Thus, attention mechanisms provide an important factor to consider when examining the processing of different stimuli in working memory, both for younger and older samples.

6.3.4 INFLUENCE OF ATTENTIONAL SCALING ON RESPONSE GENERATION

We suggest that the data best fit with the assumption that bound information is provided by attending features (Cowan et al., 2013). As attention is directed toward objects, associated object features are more likely to be co-represented. Speculatively, such a processing gain (e.g., Boynton, 2005) could influence the response process participants generate when judging the probe (Snodgrass & Corwin, 1988). As shortly introduced in the context of Experiment 4, some models of response generation suggests that a final decision to a two-alternative forced-choice task is the result of a continuous collection of evidence for one of the two choices. On a very basic level, such drift diffusion models (see, Ratcliff, Smith, Brown, & McKoon, 2016, for a review on drift diffusion models) assume that participants generate a response function that “meanders” between thresholds that lead to acceptance of one of two alternatives, given in a forced-choice task such as administered in the present thesis. As long as no threshold value has been crossed, the respondent cannot make a decision. Increasing the weight (or gain) of a specific feature might influence the course of this function and thus lead to faster or less diffuse response processes (for a detailed entry to drift diffusion models, see, e.g., Wagenmakers et al., 2007). Findings from the sub group comparison in the indirect task of Experiment 4 could fit these assumptions: depending on a potentially proactive or reactive strategy, task-irrelevant intrinsic color feature changes can experience a specific processing gain that influences the target evaluation process. A significant mismatch signal can be used to positively influence this processes, hypothetically contributing to a more unequivocal response generation process. Hence, the difference between intrinsic and extrinsic feature processing is to a substantial amount determined by early attentional selection effects: intrinsic features experience a significant gain, as soon as other integral features, such as the shape, are selected by attention. Clearly, Experiment 4 was not designed to answer this question; future research is needed to investigate the role of early ERP mismatch effects on decision making processes.

7 CONCLUSION

This dissertation project was set out to investigate how the distribution of intrinsic and extrinsic visual information across objects influences WM performance. Following the LTM framework of the type-token model (Ecker et al., 2007b), we set out with the assumption that the processing advantage of intrinsic over extrinsic information in WM is based on different binding mechanisms, mediated via different neural structures. To this end, the intentional and unintentional formation of intrinsic and extrinsic shape-color bindings was assessed in variants of a change detection task: we contrasted the intentional and unintentional processing of shape-color combinations in a direct test for association memory and an indirect test using effects of task-irrelevant feature changes, respectively.

In the first two experiments, we found that the distinction between intrinsic and extrinsic stimuli has been proven to be of significant importance for WM, as stimulus type influenced WM performance across all test conditions. However, although extrinsic binding performance was more susceptible to age-related deteriorative effects, we found that such deficit could be compensated if the extrinsic binding information was intentionally heeded. Moreover, we could show that intrinsic and extrinsic binding processes were not engaged with different temporal structure across the lifespan. We argued, that intact hippocampal functioning is of subordinate importance for intrinsic and extrinsic binding in WM. Instead, we found clear indications for a more general extrinsic feature processing deficit that was observed to be more pronounced in old age.

In a third experiment, we found that intrinsic and extrinsic feature associations did not differentially influence the maintenance process of the corresponding WM representations. We argued that both stimulus types can be represented as integrated entities once transferred to WM.

However, findings from a fourth experiment yielded compelling evidence that—in contrast to our initial assumptions—early selection effects based on attentional processes rather than different binding mechanisms are of critical importance for the distinction between intrinsic and extrinsic information processing. ERPs related to mismatch detection (N2, FN400) and later probe evaluation (P3-like positive component latencies) indicate that the adaption of the focus of attention to different visual formats provides a key function that determines differences in the ease of intrinsic and extrinsic feature processing. The processing advantage of intrinsic over extrinsic information is, thus, most likely the result of intrinsic information experiencing some form of processing gain as soon as attention is directed toward the outline of the to-be-remembered object. Extrinsic information makes a modulation of the focus of attention necessary.

In general, feature integration into object representations is not obligatory und all conditions and object representations can be incomplete. Intrinsic but not extrinsic features experiencing an increased likelihood to be represented as soon as some object information is attended. Although potentially relying on the integrity of hippocampal functioning, differences in intrinsic and extrinsic information processing in WM could be more closely related to attentional modulation than dedicated binding mechanisms than initially assumed. Within the framework of the available data, we suggest that this contributes to a detachment of our concept of "working memory" from a time-oriented separated entity with specialized neural structures to a more task-oriented network in close interaction to perception and attention (Gao et al., 2011; Zimmer, 2008).

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9 APPENDIX 1: VISUAL SEARCH TASK OF EXPERIMENT 1

The design of the search task to estimate the presentation time of the stimuli in Experiment 1 was a fully crossed 2 (stimulus type: extrinsic, intrinsic) × 2 (set size: 4, 9) design, with the target being present in 50% of the trials. The task consisted of eight blocks with 10 trials each. Conditions appeared in random order.

9.1 MATERIALS AND APPARATUS

The same shape stimuli as used in the main Experiment 1 were presented in the search task, except that shapes were always presented in white color in both extrinsic and intrinsic format. Proper encoding was thus estimated according to the more complex shape information (Alvarez & Cavanagh, 2004).

9.2 PROCEDURE

Participants were required to indicate whether a target shape was present or absent from a display of four or nine stimuli. Each trial began with the presentation of a fixation cross for 400 ms, which changed to an "x" for an interval of between 650 and 950 ms (exact duration was randomly determined) and then changed back to a fixation cross for another 400 ms. Thereafter, the target stimulus was presented for 500 ms at the center of the screen. After a blank interval of 900 ms, the search array of four or nine stimuli was presented and remained on-screen until a response was given, or for a maximum of 5,000 ms. Stimuli of the search array were randomly positioned in an invisible 3 × 3 grid. Participants made a present/absent response by pressing a key on a Cedrus response pad (RB-834, Cedrus Corporation, San Pedro, California, USA). Response categories were assigned according to the handedness of the participant, with target-present responses mapped onto the dominant hand. Both accuracy and response speed was emphasized. To ensure adequate understanding of the paradigm, all participants performed eight practice trials that were not included in later data analyses.

Encoding time per item (*ETI*) was estimated by calculating the mean RT for correct trials separately for each search array size, and then calculating a measure of search slope: $ETI = (mean\ RT_{9\ \mathrm{Items}} - mean\ RT_{4\ \mathrm{Items}})\ /\ 5$ (see Alvarez & Cavanagh, 2004). Presentation time for the three study items of Experiment 1 was then set to *3 × ETI + action onset time*. The action onset time was a constant time provided for action initiation and task set implementation. It was calculated as the mean RT for nine items minus the estimated search time for nine items, that is $mean\ RT_{9\ \mathrm{Items}} - (ETI \times 9)$.

9.3 RESULTS

Trials were excluded prior to analyses according to the same scheme applied to the main Experiment 1, resulting in the exclusion of 0.47% of the trial data. Descriptive statistics for accuracies and RT are given in Table 7.

Table 7: Recognition performance and response times for younger and older adults in the search task in Experiment 1

			Younger		**Older**	
			ACC	**RT**	**ACC**	**RT**
Stimulus	**Set size**	**Target**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**
Extrinsic	4	absent	.98 (.05)	2,202 (464)	.88 (.14)	2,839 (526)
		present	.90 (.10)	1,466 (366)	.89 (.10)	1,770 (346)
Intrinsic		absent	.98 (.04)	1,242 (277)	.93 (.08)	1,642 (287)
		present	.93 (.08)	1,055 (243)	.94 (.08)	1,277 (247)
Extrinsic	9	absent	.97 (.06)	2,210 (489)	.88 (.13)	2,815 (567)
		present	.90 (.11)	1,465 (421)	.88 (.11)	1,798 (359)
Intrinsic		absent	.97 (.05)	1,216 (262)	.94 (.07)	1,640 (283)
		present	.93 (.09)	1,009 (231)	.93 (.10)	1,272 (272)

Note. ACC = accuracy; RT = response time in ms.

Overall, participants solved the search task with high accuracy. Older adults had slightly lower performance, $M = .91$, $SE = .006$, than younger adults, $M = .94$, $SE = .006$, $U = 519.50$, $z = -3.75$, $p < .001$, but the differences between conditions were minor.

The analysis of RTs revealed a different pattern. RT data were analyzed in a 2 × 2 × 2 × 2 mixed-measures ANOVA with the within-subjects factors set size (4/9), stimulus type (extrinsic/intrinsic), and target type (absent/present), and the between-subjects factor age group (young/old). No main effect of set size was observed, $F < 1$. RTs were longer for extrinsic stimuli, $M = 2{,}071$, $SE = 40$, than for intrinsic stimuli, $M = 1{,}294$ ms, $SE = 25$, with $F(1, 86) = 1{,}248.91$, $p < .001$, $\eta_p^2 = .94$. Target-absent trials, $M = 1{,}976$ ms, $SE = 39$, had longer RTs than target-present trials, $M = 1{,}389$ ms, $SE = 28$, with $F(1, 86) = 479.56$, $p < .001$, $\eta_p^2 = .85$. Older adults, $M = 1{,}882$ ms, $SE = 45$, had longer RTs than younger adults, $M = 1{,}483$ ms, $SE = 44$, $F(1, 86) = 39.79$, $p < .001$, $\eta_p^2 = .32$. Moreover, there was a significant interaction of stimulus type and age, with $F(1, 86) = 10.51$, $p = .002$, $\eta_p^2 = .11$: the RT difference between intrinsic and extrinsic stimuli was larger for older adults, $M = 848$ ms, $SE = 31$, than for younger adults, $M = 706$ ms, $SE = 31$. The interaction of target type and age was also significant, $F(1, 86) = 19.43$, $p < .001$, $\eta_p^2 = .18$, indicating that the difference between target-present and target-absent trials was greater for older adults, $M = 705$ ms, $SE = 38$, than for younger adults, $M = 469$ ms, $SE = 38$. Finally, stimulus type and target type interacted, $F(1, 86) = 248.63$, $p < .001$, $\eta_p^2 =$

.74. The RT difference between intrinsic and extrinsic stimuli was larger for target-absent trials, *M* = 1,082 ms, *SE* = 33, than for target-present trials, *M* = 472 ms, *SE* =25.

9.4 DISCUSSION

The data were as expected. Participants across both age groups showed high levels of performance. However, older participants had longer RTs, and this effect was more pronounced if the perceptual task was difficult. Thus, older participants were given longer encoding times in Experiment 1, adapted to their personal search time, in order to compensate for perceptual slowing.

10 APPENDIX 2: ANALYSES TO THE LPC OF EXPERIMENT 4

10.1 STATISTICAL ANALYSES TO THE LPC-LIKE OLD-NEW EFFECTS FROM 500 TO 800 MS IN THE DIRECT TEST

A repeated-measures 2 × 2 × 2 × 2 ANOVA on mean amplitudes of difference waves with factors area (frontal/parietal), hemisphere (left/right), stimulus type (intrinsic/extrinsic), and change type (new shape/new color) revealed a main effect of change type, $F(1, 23) = 8.86$, $p = .007$, η_p^2 = . 28, which was qualified by an interaction with stimulus type, $F(1, 23) = 5.40$, $p = .029$, η_p^2 = . 19. Pairwise comparisons revealed that for extrinsic stimuli, color changes, $M = -1.33$ µV, 95% CI [-2.35, -0.31], $SE = 0.494$, elicited a more negative going difference wave than shape changes, $M = 0.01$ µV, 95% CI [-0.70, 0.71], $SE = 0.340$, $p_{\text{Bonferroni}} = .001$. For intrinsic stimuli, color changes, $M = -0.98$ µV, 95% CI [-1.89, -0.06], $SE = 0.443$, and shape changes, $M = -0.49$ µV, 95% CI [-1.26, 0.28], $SE = 0.371$, elicited comparable difference waves, $p_{\text{Bonferroni}} = .211$. No other main effect or interaction reached significance (smallest p-value for the interaction of hemisphere and change type, $F[1, 23] = 1.73$, $p = .201$, $\eta_p^2 = .07$). For intrinsic stimuli, old-new effects in terms of LPC-like ERPs were observed for incongruent shapes and colors if both features were task-relevant. For extrinsic stimuli, changes to color but not shape features elicited a LPC-like ERP. ERPs were not restricted to the expected parietal area.

10.2 STATISTICAL ANALYSES TO THE LPC-LIKE OLD-NEW EFFECTS FROM 500 TO 800 MS IN THE INDIRECT TEST

A repeated-measures 2 × 2 × 2 × 2 ANOVA on difference waves with factors area (frontal/parietal), hemisphere (left/right), stimulus type (intrinsic/extrinsic), and change type (no-change minus shape change/irrelevant change minus shape change) yielded a significant interaction of area and change type, $F(1, 23) = 5.67$, $p = .026$, $\eta_p^2 = .20$, suggesting that the mean difference between difference waves based on no-change references and irrelevant-color-change references was larger at parietal areas, $M_{\text{Difference}} = -.513$ µV, 95% CI [-1.18, 0.15], $SE = .322$, than at frontal areas, $M_{\text{Difference}} = -.055$ µV, 95% CI [-0.87, 0.76], $SE = .394$. There was a significant three-way interaction of area, hemisphere and stimulus type, $F(1, 23) = 7.27$, $p = .013$, $\eta_p^2 = .24$. No other main effect or interaction reached significance, with the smallest p-value for the interaction of hemisphere and stimulus type, $F(1, 23) = 2.55$, $p = .124$, $\eta_p^2 = .10$. These results were unexpected for the investigation of LPC-like old-new effects, as change type did not influence the waveforms.

For parietal areas, the 2 × 2 × 2 repeated-measures ANOVA on difference waves with factors hemisphere (left/right), stimulus type (intrinsic/extrinsic), and change type (no change minus shape change/irrelevant change minus shape change) yielded no significant main effects or interactions, with the smallest p-value approaching of marginal significance for the main effect of change type, $F(1, 23) = 2.54$, $p = .124$, $\eta_p^2 = .10$. Again, these results were unexpected, as change type did not influence the old-new effect, again allowing for no sharp distinction between new and old items.

11 APPENDIX 3: N2 ANALYSES TO EXPERIMENT 3

Analyses were conducted to investigate whether probe-related N2 mismatch effects observed in Experiment 4 also occurred in Experiment 3. To this end, we re-analyzed the data of Experiment 3 stimulus-locked to the onset of the probe. For comparison, this analysis is based on the logic applied to the data from Experiment 4. We expected that detection of a change (shape change/color change) was accompanied by a more negative N2 signal compared to no-change trials, for intrinsic and extrinsic stimuli.

11.1 METHODS

Due to excessive ocular artifacts during the test phase of Experiment 3, one additional participant was excluded from the data analyses. Thus, data of n = 26 was investigated.

To investigate early N2 mismatch effects, the continuous electrophysiological signal was segmented into epochs averaging from -200 ms to +1300 ms stimulus-locked to the onset of the probe. Trials with wrong or missed responses were neglected. A baseline correction using the time period 200 ms before test display onset was applied to the epochs. A high-pass filter of 0.1 Hz, 24 dB/octave as well as a low-pass filter of 30 Hz, 12 dB/octave, were applied as recommended by Luck (2014). Eye-movement and blink correction was done according to Gratton et al. (1983). In addition, epochs containing artifacts not related to blinking were rejected before averaging according to the following criteria: maximal allowed voltage step between two successive sampling points: 30 µV; maximal allowed difference of values in an interval of 200 ms: 150 µV; maximum amplitude in the recording epoch: ±100 µV, lowest allowed activity within an interval of 100 ms: 0.5 µV. This procedure led to the loss of on average 8.94% of the epoch data.

As in Experiment 4, statistical analyses of the N2 focused on Fz. Neurophysiological correlates of mismatch detection were evaluated as a peak-to-peak analysis from the P2 to the N2 component. Therefore, the same time windows for the local maxima of the P2 an N2 amplitudes as used in Experiment 4 were investigated. The N2 mismatch effect was then quantified as the differences between the peak amplitudes of N2 and P2 for each condition, and averaged across participants.

11.2 RESULTS AND DISCUSSION

Corresponding ERP waves can be found in *Figure 28*. For the shape test, P2-N2 peak-to-peak amplitude differences at Fz were entered in a 2 × 3 repeated measures ANOVA with factors stimulus type (monochrome/intrinsic/extrinsic), and change type (no change/new shape). The analysis yielded a marginal significant main effect of change type, *F*(1, 25) = 3.68, *p* = .066, η_p^2 = .13, suggesting that trials with a changed shape feature elicited a numerically more negative ongoing signal, *M* = -4.89 µV, 95% CI [-5.84, -3.93], *SE* =.46, compared to trials with no feature change, *M* = -4.17 µV, 95% CI [-5.12, -3.22], *SE* =.46. Neither the main effect of stimulus type, *F* < 1, nor the interaction of both factors, *F*(2, 50) = 1.56, *p* = .220, η_p^2 = .06, reached the statistical significance level of *p* = .05. Comparable to the results of Experiment 4, if participants had to attend to only the shape of the object, we observed a tendency of a change to produce a more negative ongoing wave compared to trials when no change happened. Yet, the pattern of the color information (monochrome, intrinsic, or extrinsic) did not influence the mismatch signal. It is, however, important to note that Experiment 3 was not designed to test an irrelevant-change distraction effect. Hence, we cannot draw any conclusions about the obligatory processing of the color information.

For the shape and color test, P2-N2 peak-to-peak amplitude differences were entered in a 2 × 2 repeated measures ANOVA with factors stimulus type (intrinsic/extrinsic) and change type (no change/new feature [color or shape]). The analysis yielded a significant main effect of change type, *F*(1, 25) = 4.26, *p* = .049, η_p^2 = .15, indicating that trials with a changed shape or color feature elicited a more negative ongoing signal, *M* = -4.56 µV, 95% CI [-5.58, -3.53], *SE* =.50, compared to trials with no feature change, *M* = -3.88 µV, 95% CI [-4.98, -2.78], *SE* =.53. There was no main effect of stimulus type and no significant interaction of both factors, with both *F* < 1. Similar to the findings from Experiment 4, if participants intentionally stored intrinsic and extrinsic shape-color associations, feature changes elicit a more negative N2 compared to no change trials. Due to the imbalanced trial numbers, however, shape and color changes were aggregated in the present analysis, as it was not the initial goal of Experiment 3 to distinguish between their effects at the time of test.

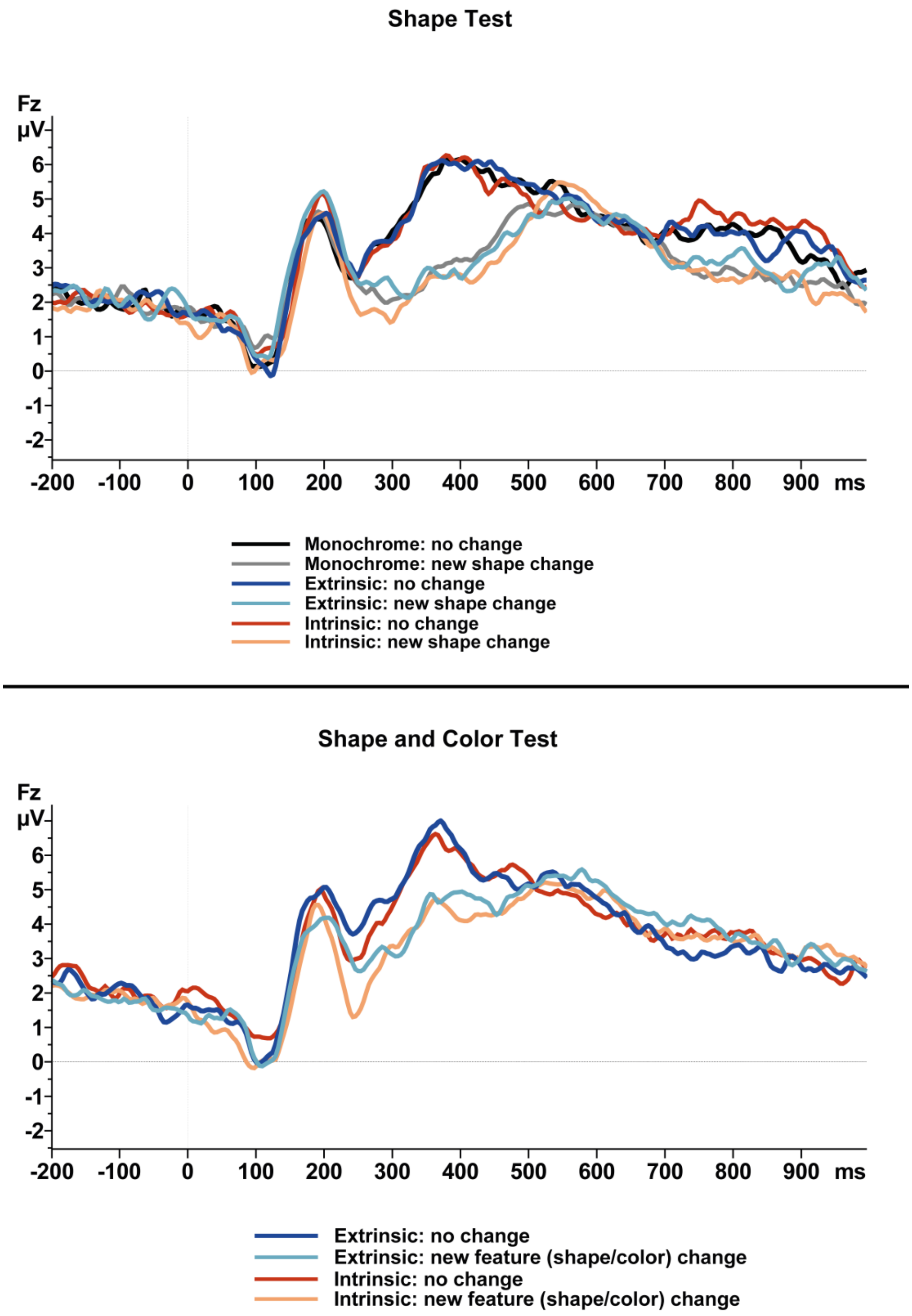

Figure 28: Grand-average waveforms for the three stimulus types and change conditions in the shape test (top) and the shape and color test (bottom) of Experiment 3 displayed for the Fz electrode site. Waveforms are aligned to the test stimulus onset.

Overall, we observed similar incongruence effects for the change of object features in Experiment 3 that were also observed in Experiment 4. We thus assume that we were able to observe comparable neurophysiological effects related to mismatch, especially if participants intentionally attended the shape-color association.

12 ZUSAMMENFASSUNG IN DEUTSCHER SPRACHE

Das visuelle Arbeitsgedächtnis (AG) hält eine begrenzte Menge visueller Information für die menschliche Kognition für einen umschriebenen Zeitraum mental aufrecht, wenn die korrespondierende Information in der physikalischen Umgebung nicht länger verfügbar ist. Somit kann die Information für weitere kognitive Aufgaben genutzt werden. Zur Untersuchung der Eigenschaften des visuellen AG wird häufig das Change Detection Paradigma genutzt. Bei dieser Aufgabe werden Probanden aufgefordert, eine definierte Menge an Informationen im AG aufrechtzuhalten. Nach einem kurzen Behaltensintervall, während dessen die zu behaltende Information nicht länger zur Verfügung steht, werden die Probanden gebeten, neu präsentierte Informationen mit der im AG repräsentierten Information zu vergleichen. Die Probanden sollen angeben, ob die neue Information gleich oder verschieden zu der zuvor präsentierten Information ist.

Einige Modelle zur Funktionsweise des visuellen AG postulieren, dass integrierte Objekte im AG repräsentiert werden. Entsprechend dieser objekt-basierten Betrachtung des AGs werden entweder alle Objektinformation behalten oder alle Objektinformation vergessen. In der physischen Umgebung bestehen visuelle Objekte jedoch aus zahlreichen Merkmalen, Elementen oder Teilen. Mehrere Studien konnten bereits zeigen, dass das visuelle AG davon beeinflusst wird, wie die zu repräsentierenden visuellen Merkmale über das Objekt verteilt sind. Informationen die zu einem gemeinsamen Objektteil gehören werden besser erinnert, als Informationen die z.B. zu verschiedenen Objekten oder Objektteilen gehören. Ziel der vorliegenden Dissertation war die Untersuchung, ob dieser Effekt auf unterschiedlichen Bindungsmechanismen für die Integration inhärenter und disjunkter Objektmerkmale basiert.

Die Ausrichtung des Dissertationsprojektes basierte dabei auf Befunden der Langzeitgedächtnisforschung. Im Rahmen des Typ-Token Modells (Zimmer & Ecker, 2010) konnte gezeigt werden, dass mindestens zwei verschiedene Bindungsmechanismen am Transfer visueller Information in eine Langzeitgedächtnisrepräsentation beteiligt sind. Intrinische Bindungsmechanismen vermitteln dabei objekt-inhärente Informationen, extrinsische Bindungsmechanismen werden benötigt um kontextuelle oder objekt-disjunkte Merkmale in eine Repräsentation zu überführen. Entsprechend des Type-Token Modells (Zimmer & Ecker, 2010) wird angenommen, dass die intrinsische Bindungsmechanismen eher automatisch und über die Perzeption erfolgen und somit obligatorisch objekt-inhärente Merkmale in eine Repräsentation ins Langzeitgedächtnis überführt. Diese Repräsentation wird als Objekt-Token bezeichnet

(Zimmer & Ecker, 2010). Wurde das Perzept in eine Gedächtnisrepräsentation überführt, kann dieses Objekt-Token gegen neue, perzeptvermittelte, intrinsisch gebundene Information verglichen werden. Letzteres wird ebenfalls als eher automatischer Prozess beschrieben. Extrinsische Bindung bezieht sich hingegen auf einen Mechanismus, der disjunkte Einheiten, z.B. einzelne Objekt-Token, in Perzeption und Gedächtnis bindet. Es wird angenommen, dass es sich dabei um einen bewusst initiierten Prozess handelt. Der Prozess resultiert in der Speicherung höhergeordneter Episoden-Token, die somit individuelle Einheiten mit Kontextinformation anreichern. Neurophysiologisch ließ sich außerdem zeigen, dass die Bindung intrinsischer Merkmale über perirhinale Strukturen vermittelt wird, während die extrinsische Bindung auf die intakte Funktion des Hippocampus angewiesen ist.

Es ist jedoch wenig darüber bekannt, ob intrinsische und extrinsische Bindungsmechanismen auch im AG die Verarbeitungsunterschiede zwischen unterschiedlichen Objektmerkmalen erklären. Analog zu Modellen des Langzeitgedächtnisses nahmen wir für die Planung der Experimente an, dass intrinsische Merkmalsbindung eher automatisch als ein Nebenprodukt der Perzeption erfolgen kann, während Mechanismen zur Bindung extrinsische Objektmerkale supplementär initiiert werden müssen und somit eher nur dann erfolgen, wenn die Aufgabe es erfordert.

In einer Reihe von vier Experimenten konnten wir zeigen, dass das visuelle AG nicht unter allen Bedingungen integrierte Objekte repräsentiert. Unsere Ergebnisse legen nahe, dass intrinsische, nicht jedoch extrinsische Objektinformationen ohne Intention in eine Objektrepräsentation integriert werden können. Im Gegensatz zu Erkenntnissen der Langzeitgedächtnisforschung scheinen diese Effekte im AG jedoch nicht primär die Folge unterschiedlicher Bindungsmechanismen zu sein. Wir argumentieren, dass die Skalierung des Fokus der Aufmerksamkeit basierend auf der visuellen Beschaffenheit der zu behaltenden Objekte, einen entscheidenden Faktor für den Verarbeitungsvorteil intrinsischer verglichen mit extrinsischer Objektinformation darstellt.

In Experiment 1 untersuchten wir dazu, ob die Speicherung von intrinsischen Objektmerkmalsbindungen ein eher kostenfreier Prozess ist und die extrinsische Bindung eine für das AG anspruchsvollere Aufgabe darstellt. Wir nahmen an, dass intrinsische Informationen unabhängig von den Aufgabenanforderungen automatisch in eine AG Repräsentation integriert werden, während die Bindung von extrinsischen Merkmalen bewusst aktiviert werden muss. Darüber hinaus wurde untersucht, ob die extrinsische Bindung im AG stärker als die intrinsische Bindung auf die intakte Hippocampusfunktion angewiesen ist. Zu diesem Zweck haben wir uns auf den

Vergleich zwischen einer jüngeren und einer älteren Stichprobe konzentriert, da der Hippocampus als einer der ersten Bereiche von altersbedingter Degenerationsprozesse betroffen ist. Bindungsunterschiede zwischen intrinschen und extrinsischen Objekten sollten somit im höheren Alter deutlicher werden. In Experiment 1 verglichen wir daher das die Arbeitsgedächtnisleistung für Merkmalsverknüpfungen sowie einzelne Merkmale einer jüngeren (18-33 Jahre) und einer älteren (64-82 Jahre) Stichprobe. Im Rahmen einer Change Detection Aufgabe wurden die Probanden instruiert, komplexe farbige Formen zu merken. In einem direkten Test sollten die Probanden die Farb-Form-Assoziationen behalten; in einem indirekten Test sollten die Probanden nur die Formen im AG aufrechterhalten, die Farben waren irrelevant für die Aufgabe. Wir interessierten uns für die entstehenden Kosten, wenn aufgabenirrelevante Farbänderungen von Lern- zu Testzeitpunkt ignoriert werden mussten.

Im direkten Test zeigte sich insgesamt eine erwartete niedrigere Arbeitsgedächtnisleistung für intentional behaltene Assoziationen, wenn extrinsische statt intrinsische Bindung erforderlich war. Zudem fanden wir bei älteren Probanden eine generell schlechtere Arbeitsgedächtnisleistung. Es wurde jedoch kein altersbedingtes Bindungsdefizit, weder für intrinsische, noch extrinsische Form-Farbe-Assoziationen beobachtet. Im indirekten Test zeigte sich hingegen eine Interaktion von Bindungstyp und Altersgruppe: Jüngere Probanden zeigten Lern-Test-Kongruenz-Effekte unabhängig von der Art der geforderten Bindung, ältere Probanden zeigten erhöhte Kongruenz-Effekte für intrinsische Stimuli. Letzteres weist auf eine intakte intrinsische Bindung hin; die praktisch fehlenden Kosten für extrinsische aufgabenirrelevante Merkmalsveränderungen deuten auf einen beeinträchtigten extrinsischen Bindungsmechanismus hin. Dieser stimulusspezifische Effekt einer aufgabenirrelevanten Merkmalsänderung zeigt, dass die Verarbeitung intrinsischer und extrinsischer Merkmale im AG durch gesundes Altern unterschiedlich beeinflusst werden. Unter intentionaler Enkodierung waren ältere Probanden außerdem in der Lage, mögliche Verarbeitungsdefizite zu kompensieren. Zudem konnte der Verarbeitungsvorteil intrinsischer Information gegenüber extrinsischer Information sowohl für einzelne Merkmale als auch für deren Bindung beobachtet werden. Die unterschiedliche Integration von extrinsischen und intrinsichen Informationen kann somit das Ergebnis altersbedingter Veränderungen früher Selektionsmechanismen sein, wenn visuelle Information in das Arbeitsgedächtnis enkodiert wird, oder das Ergebnis von Änderungen späterer Bindungsprozesse, wenn Informationen im WM konsolidiert werden. Letzteres prüften wir in einem zweiten Experiment.

Experiment 2 leg nahe, dass altersbedingte Verarbeitungsdefizite extrinsischer Bindungsinformation eher nicht die Folge einer altersbedingten Beeinträchtigung des Bindungsmechanismus selbst ist. In Experiment 2 manipulierten wir die Präsentationszeit der zu erinnernden intrinsischen und extrinsischen Merkmalsbindungen. Wenn die extrinsische Bindung einen Mechanismus darstellt, der der intrinsischen Bindung nachgelagert ist, kann erwartet werden, dass die extrinsische Bindung zeitabhängiger ist als die intrinsische Bindung.

Wir fanden keine Hinweise darauf, dass die Interaktionen zwischen der Bindung von intrinsischen und extrinsischen Form-Farbe-Assoziationen und der verfügbaren Zeit zur Konsolidierung der Informationen durch das Alter unterschiedlich beeinflusst wurde. Stattdessen legt Experiment 2 nahe, dass der altersbedingte Rückgang extrinsischen Bindungsleistung Folge einer eher generalisierten Reduktion der Repräsentation extrinsischer Merkmalsinformation ist.

Ziel von Experiment 3 war es, zu untersuchen, ob intrinsische und extrinsische Assoziationen unterschiedliche Anforderungen an die kurzfristige Aufrechterhaltung der Repräsentationen während des Behaltensintervalls stellen, sobald die Information in eine stabile AG-Repräsentation überführt wurde (vgl. *Figure 27*). Mit einer bilateralen Version der Change Detection Aufgabe untersuchten wir die Contralateral Delay Activity (CDA) während des Behaltensintervalls. Die CDA wird dabei als das neurophysiologische Korrelat der Behaltensanforderungen einer Information im AG diskutiert.

Nicht deckungsgleich zu den behavioralen Befunden unterschieden sich die mittleren Amplituden der CDA für intrinsische und extrinsische Form-Farbe-Assoziationen in Experiment 3 nicht. Wir interpretieren dieses Ergebnis dahingehend, dass sowohl intrinsische als auch extrinsische Informationen als integrierte Einheit aufrechterhalten werden können, sobald sie in eine stabile Repräsentation überführt wurden. Die Daten legen nahe, dass Aufrechterhaltungsprozesse während der Retention nur unwesentlich zu Leistungsunterschiede im Arbeitsgedächtnis zwischen intrinsischen und extrinsischen Objekten beitragen.

Experimente 1 und 2 zeigten, dass intrinsische Informationen unwillkürlich Teil der Repräsentation sind, die zur Evaluation des Teststimulus genutzt wird. Diese Interpretation basiert auf der behavioralen Rekognitionsleistung, die jedoch nur das Endergebnis einer Prozesskette widerspiegelt. Experiment 4 wurde durchgeführt, um zu untersuchen, ob frühe neurophysiologische Signale der Mismatch-Detektion den Unterschied zwischen der fast automatischen Repräsentation intrinsischer Information und der intentionalen Repräsentation extrinsischer Informationen nachvollziehen. Dabei konnte gezeigt werden, dass intrinsische, jedoch nicht extrinsische Objektmerkmale, obligatorisch frühe Prozesse der Stimulusevaluation beeinflussen und so möglicherweise zu dem Verarbeitungsvorteil beitragen.

Die Arbeitsgedächtnisleistung wurde in einem direkten Test—bei dem die Probanden intentional Form-Farbe-Assoziationen behalten mussten—und einem indirekten Test—bei dem die Probanden nur die Form, aber keine Farbinformationen behalten mussten—verglichen. In der kritischen Bedingung wurden intrinsische oder extrinsische Farbinformationen vom Lern- zum Testzeitpunkt verändert. Im direkten Test zeigte die gemessene elektrophysiologische Aktivität zum Zeitpunkt des Beginns der Teststimuluspräsentation, dass Veränderungen sowohl intrinsischer als auch extrinsischer Farbmerkmale frühe ereigniskorrelierte Potentiale der Mismatch-Detektion evozieren. Im Gegensatz dazu führten nur Veränderungen intrinsischer, nicht jedoch extrinsischer Farbmerkmale in der indirekten Testbedingung zu einem Mismatch-Signal. Wird die Aufmerksamkeit des Beobachters auf die Form eines Objektes gelenkt erfahren intrinsische jedoch nicht extrinsische Merkmale einen Verarbeitungsvorteil. Extrinsische Informationen machen eine Anpassung des Fokus der Aufmerksamkeit notwendig. Darüber hinaus wurde festgestellt, dass die Amplitudenstärke der intrinsischen Mismatch N2 spätere Prozesse der Stimulusverarbeitung beeinflusst. Dies spiegelte sich in Änderungen in der Latenzzeit einer P3-ähnlichen positiven Komponente widerspiegelte, welche mit Entscheidungsprozessen zur Stimulusevaluation in Verbindung egbacht wird. Die obligatorische Verfügbarkeit intrinsischer Merkmalsinformation könnte so zu einem eindeutigeren Entscheidungsfindungsprozess und in der Folge zu dem beobachteten Verarbeitungsvorteil beitragen.

Die Ergebnisse des vorliegenden Dissertationsprojektes replizieren frühere Befunde über einen Verarbeitungsvorteil intrinsischer gegenüber extrinsischer Objektinformation. Darüber hinaus legen unsere Befunde nahe, dass dieser Verarbeitungsvorteil nicht das Ergebnis unterschiedlicher Bindungsmechanismen ist, wie es für Langzeitgedächtnisprozesse angenommen werden kann. Wir argumentieren, dass die Verteilung visueller Informationen insbesondere die Skalierung des Fokus der Aufmerksamkeit beeinflusst. Objektinhärente intrinsische Merkmale gewinnen durch die Ausrichtung der Aufmerksamkeit auf das Objekt einen Verarbeitungsvorteil, sodass die Wahrscheinlichkeit erhöht wird, dass die intrinsische Information in eine Arbeitsgedächtnisrepräsentation überführt wird. Für extrinsische Objektmerkmale, die Bestandteile des direkten Objektkontexts sind, kann ein zusätzlicher Skalierungsprozess des Fokus der Aufmerksamkeit notwendig sein. Wir interpretieren diese Ergebnisse im Sinne des von Cowan, Blume und Saults (2013) vorgeschlagen Modells zur Repräsentation von Objekten im Arbeitsgedächtnis: Die visuelle Arbeitsgedächtniskapazität ist auf eine umgrenzte Anzahl von Objekten beschränkt, aber diese Objektrepräsentationen können je nach Wirkungsrichtung der Aufmerksamkeit unvollständig sein.