

**Task Demands Differentially Affect Processing of Intrinsic and Extrinsic Object
Features in Working Memory: Electrophysiological Evidence for an Intrinsic
Processing Advantage**

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Word count: approx. 6,975 (main text including figures and tables)

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Abstract

Some argue that visual working memory operates on integrated object representations. Here we contend that obligatory feature integration occurs with intrinsic but not extrinsic object features. Working memory for shapes and colors was assessed using a change-detection task with a central test probe, while recording event-related potentials (ERPs). Color was either an intrinsic surface feature of a shape or connected to the shape via a proximal but spatially-disjunct extrinsic frame. There were two types of test: The direct test required memory for shape and color; the indirect test required only shape memory. Study-test changes of color were therefore either task-relevant or task-irrelevant. We assessed performance costs and ERP effects arising from color changes. In the direct test, performance was poorer for extrinsic than intrinsic stimuli; task-relevant color changes elicited enhanced frontal negativity (N2, FN400) for both intrinsic and extrinsic stimuli. In the indirect test, performance costs and ERP effects associated with irrelevant color change were larger for intrinsic than extrinsic stimuli. This suggests intrinsic information is more readily integrated into the working-memory representation and evaluated against the test probe. Findings imply that feature integration is not obligatory under all conditions, but influenced by stimulus-driven and task-related focus of attention.

Keywords: working memory; feature binding; event-related potentials; N2; FN400

Task Demands Differentially Affect Processing of Intrinsic and Extrinsic Object Features in Working Memory: Electrophysiological Evidence for an Intrinsic Processing Advantage

Visual working memory (WM) is a capacity-limited system that serves to hold and manipulate visuospatial information over brief periods of time (Brady et al., 2011; Logie et al., 2021; Mance & Vogel, 2013). It is often investigated using a change-detection paradigm, in which participants are presented with a memory array for a few hundred milliseconds. After a short retention interval, a test array is presented, and participants are required to judge whether the test array matches the study array, or whether it has changed. The to-be-remembered information can vary from simple features (e.g., color patches) to more complex multi-featured objects (e.g., abstract colored shapes). In the latter case, all features (e.g., color and shape) can be deemed task-relevant or only specific features (e.g., just shapes but not the associated colors). The manner in which these manipulations influence memory performance is controversially debated. Two extreme theoretical positions can be identified, which—in principle—define a continuum.

At one end of the continuum, the object-based position assumes that the object is the unit of representation, with the number of to-be-remembered objects being critical for memory performance. According to this view, objects are encoded in their entirety (i.e., with all features) and WM can store up to three or four such units (Adam et al., 2017; Luck & Vogel, 1997; for a review, see Brady et al., 2011). Sometimes it is additionally assumed that objects and their features are also forgotten in an all-or-none manner (e.g., Gajewski & Brockmole, 2006). At the other end of the continuum, the feature-based position assumes that features are the units and that memory is limited due to competition between feature representations (e.g., Bays et al., 2009; Ma et al., 2014; Oberauer, 2021; Schneegans et al.,

2020; Wilken & Ma, 2004; also see Wang et al., 2017). As a consequence, features can also be forgotten independently (Bays et al., 2011; Fougnie & Alvarez, 2011).

In-between these two extreme positions, some authors suggest that both objects and features produce WM load and that feature encoding is not obligatory but depends on the task demands and the perceptual structure of the stimulus (e.g., Fougnie et al., 2010; also see Swan et al., 2016). According to this view, memory performance depends on the task-relevance of features, while objects also play a specific role inasmuch as the distribution of features across objects in the perceptual field has an independent influence on memory. For example, spatial proximity as well as hierarchical stimulus organization influence binding of features (Emrich & Ferber, 2012; Vul et al., 2020). We likewise argue that perceptual structure has an effect on WM performance independent of task demands; this is in line with the observation that memory is generally better for features that belong to the same object rather than features distributed across different objects (Fougnie et al., 2010; Xu, 2002a, 2002b, 2006).

The Processing of Intrinsic Versus Extrinsic Features

The focus of the present experiment is on the above-mentioned object advantage; specifically, we manipulated task demands to show that intrinsic and extrinsic features are differentially processed in WM. Intrinsic features are features that are inherent to a perceptual object, such as an object's surface color. A sizeable literature has found that such intrinsic features can be encoded and represented in WM even if they are task-irrelevant (e.g., Gu et al., 2022; Shen et al., 2013; Zhang et al., 2013), even though there is also some evidence that representation of task-irrelevant object features tends to be low in fidelity or short-lived (e.g., Logie et al., 2011; Shin & Ma, 2016; Swan et al., 2016; Xu, 2010) and may not always occur (e.g., Serences et al., 2009; Tam & Wyble, 2022). By contrast, extrinsic features are features that are associated with an object (e.g., through spatial proximity) but are part of a separate

perceptual unit, such as the color of a frame surrounding an object (Troyer & Craik, 2000; also see Ceraso, 1985; Davachi, 2006; Frings & Rothermund, 2017; Garner, 1974; Kirmsse et al., 2018; Schmalbrock & Frings, 2022; van Geldorp et al., 2015; Zimmer et al., 2006).

Some previous research has suggested that intrinsic features are more readily encoded and represented in WM than extrinsic features. For instance, Delvenne and Bruyer (2004) found better memory for shape-texture conjunctions when texture was an intrinsic feature of the shape rather than an extrinsic feature of the shape's background. Fougny et al. (2010) presented either colored arrow heads or black arrow heads connected to colored circles, and found a memory advantage for intrinsic color. However, there are also authors who argue that configurational information is obligatorily encoded and integrated in visual WM (e.g., see Boduroglu & Shah, 2009; Vidal et al., 2005).

Tasks that are particularly well suited to investigate intrinsic versus extrinsic feature processing are tasks that involve detection of task-irrelevant changes: If encoding of intrinsic but not extrinsic features is mostly involuntary, changing a task-irrelevant intrinsic but not extrinsic feature from study to test should influence WM processing. Ecker et al. (2013) showed this for irrelevant color changes: In a task where shape was the relevant feature, changing an irrelevant surface color slowed the decision more than changing a color in the shape's background. Similar processing differences have also been observed in older adults (e.g., Kirmsse et al., 2018), as well as in long-term memory studies using behavioral (Zimmer & Steiner, 2003), brain imaging (Staresina & Davachi, 2009), or electrophysiological methods (Ecker et al., 2007a, 2007b). This suggests that intrinsic features are more likely to be processed together with the object than extrinsic features, even if they are task irrelevant.

The aim of the present study was to further substantiate these differences between intrinsic and extrinsic feature integration in visual WM by applying an irrelevant-change-detection paradigm while simultaneously recording the electroencephalogram (EEG). To this

end, we presented geometrical objects with intrinsic or extrinsic color (i.e., colored shapes vs. shapes with a colored frame) in a change-detection task with color information being either relevant or irrelevant to the task. In the former condition (shape-color task; color relevant), participants had to spot study-test changes in either color or shape; in the latter condition (shape-only task; color irrelevant), only shape was relevant but its color could change from study to test—which was, however, irrelevant for the participant’s decision and uncorrelated to the change of the relevant feature. We started from the following premise: If it is true that feature processing is determined by task demands as well as intrinsicity, irrelevant intrinsic but not extrinsic color changes should provoke electrophysiological mismatch effects. We expected such mismatch effects to emerge during relatively early stages of mnemonic object processing, rather than later stages of more strategic, decision-related processing. Specifically, we focused our attention on two event-related potential (ERP) components: the N2 and the FN400.

Event-Related Potentials and Feature Processing in WM

N2

The N2 is a negative deflection about 200 ms after stimulus onset (see Folstein & van Petten, 2008, for a review). In the visual domain, the frontal N2 (also referred to as N2b; see, e.g., Luck, 2014) is considered an indicator of 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., 2011). For example, in the Eriksen flanker task, a larger N2 is observed for trials with task-incongruent distractors than for trials with task-congruent distractors (e.g., Gehring et al., 1992; Yeung et al., 2004); in the Stroop task, the N2 is larger for incompatible compared to compatible trials (e.g., Liotti et al., 2000; West & Alain, 1999); and in S1-S2 comparison tasks, the N2 is more pronounced for change compared to no-change trials (Gao et al., 2010; Mao & Wang, 2008; Randall & Smith, 2011; Yin et al., 2011). An N2 mismatch

signal can be elicited by a variety of stimulus manipulations, such as changes to color (Gao et al., 2010; Tian et al., 2001), shape (Cui et al., 2000; Gao et al., 2010), or number (Kong et al., 2000). There is also evidence that N2 mismatch signals may be larger for task-relevant than for task-irrelevant feature changes (Wang et al., 2004). Collectively, these results suggest that processing mismatching features elicits an N2 signal. Based on this and the assumed difference in the cognitive processing of intrinsic versus extrinsic features, we expected an N2 mismatch signal for color changes with both stimulus types if color is task-relevant, but only for intrinsic changes if color is task-irrelevant.

FN400

Another ERP component that may be sensitive to irrelevant feature change in WM tasks is the FN400. The FN400 is a fronto-central negativity occurring approx. 300 to 500 ms after probe onset; it tends to be more negative for new compared to old (i.e., studied) items in long-term recognition paradigms. As such, FN400 modulations are often referred to as frontal old-new effects, and the component is considered a signature of familiarity-based recognition processes (Mecklinger & Bader, 2020; Rugg & Curran, 2007). Changes of irrelevant intrinsic but not extrinsic features have been found to modulate the FN400 (Ecker et al., 2007a, 2007b; see Zimmer & Ecker, 2010, for a review), with an irrelevant intrinsic but not extrinsic color change associated with a more negative-going ERP during recognition. We propose here that a similar effect should be observed in WM tasks. Indeed, FN400-like effects have also been reported in WM tasks (Ko et al., 2014; Saiki, 2016). For example, a direct effect of color changes on this component was reported by Bledowski et al. (2012). In a change-detection paradigm with color patches, the authors observed a frontal effect in the magneto-encephalogram that varied with the perceptual similarity between the study and probe item. Between 350 and 400 ms, the signal was most positive for identical color, it was more negative for a changed but similar color, and most negative for a clearly dissimilar color. The

authors concluded that this effect is a correlate of the neural representation of the similarity between the probe and study items. Accordingly, in the present study we expected that task-irrelevant changes to intrinsic but not extrinsic color would cause more negative fronto-central scalp potentials in the time range of the FN400 because a study-test color change reduces similarity—viz. the match to the object’s memory representation—for intrinsic but not extrinsic probes.

The Present Study

To test the effect of intrinsicity (i.e., intrinsic vs. extrinsic stimulus type) on memory-related ERP effects, we conducted a change-detection task under two conditions. In the shape-color task, color was a task-relevant feature; in the shape-only task, only shape was relevant and color 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). Task (shape-only, shape-color), stimulus type (intrinsic, extrinsic), and change type (no change, shape change, color change) were manipulated in a fully-crossed within-subjects design. Note that the shape-change condition was necessary to establish a meaningful irrelevant-color-change task, but the task relevance of shape changes was neither experimentally manipulated, nor is the concept of intrinsicity applicable to shape information; therefore, the ERP effects of shape changes were not relevant for our hypothesis.¹

Our focus was on the effects of intrinsic and extrinsic color changes, which should vary across stimulus types and tasks. In the shape-only task, an intrinsic but not an extrinsic color change should elicit mismatch effects, because only in the intrinsic case should color be

¹ It was expected that a new shape should elicit an N2 mismatch effect and the FN400 should be more negative for changed (new) shapes than for identical (old) shapes; these effects should be present across stimulus types and tasks. Results confirmed these expectations; they are reported in the Supplement, available at <https://osf.io/pfbnz>.

obligatorily processed, such that a change would make the probe dissimilar to the memory entry. We thus formulated the directed hypothesis that in the shape-only task, N2 mismatch effects should be larger for intrinsic than extrinsic color changes. We further hypothesized that intrinsic color change would produce a more enhanced negativity (i.e., a negative-going FN400 relative to the no-change condition) than extrinsic color change. By contrast, in the shape-color task, processing of color was always required irrespective of stimulus type. We therefore expected effects of color change that were comparable for both stimulus types.

In the shape-only condition, stimulus-type-dependent effects of irrelevant color change were also expected for accuracies and response times (RT; see Ecker et al., 2013). A color change should make correct recognition of an old shape slower and less likely, but only if color is intrinsic. We thus formulated the directed hypothesis that color change would be associated with larger accuracy and RT costs in the intrinsic than the extrinsic condition.

Method

Participants

A total of 26 right-handed undergraduate non-psychology students were recruited at Saarland University.² Data from two participants were discarded due to technical errors. The final sample consisted of $N = 24$ participants (14 females, 10 males), with age ranging from 18 to 29 years ($M = 23.42$, $SD = 2.81$). Participants reported normal or corrected-to-normal vision, and no color-blindness, clinical diagnosis of migraine or epilepsy, history of neurological disorder (within the last 5 years), or current intake of pharmaceuticals that could influence RTs. Participants provided written informed consent after reading an ethically-

² Sample size was determined based on the following rationale: The critical effect of interest is a planned one-sided interaction contrast with $df = 1$ (i.e., a test of the difference between incongruent and congruent features in intrinsic vs. extrinsic stimuli in the shape-only condition). This corresponds to a t -test, and power analysis ($\alpha = 0.05$; $1 - \beta = 0.80$; G*Power 3; Faul et al., 2007) suggested a sample size of 27 to detect an effect of $d_z = 0.5$ (this was incorrectly noted down as 26 at the time, potentially due to $df = 26$ in the G*Power output).

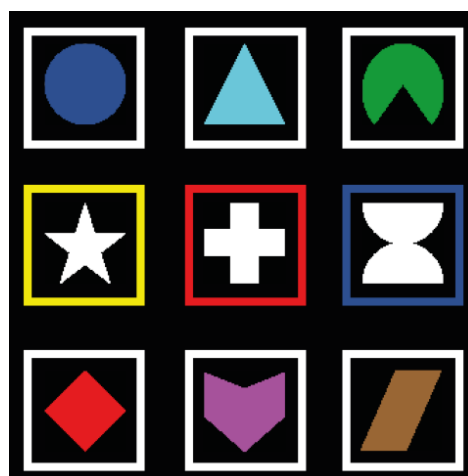
approved information sheet; they received compensation of €8 per hour. The study was approved by the ethics committee of the Faculty of Human Sciences at Saarland University.

Stimuli

The study used a set of nine geometrical shapes (see Figure 1) encased by square frames. We used seven colors: (blue [RGB values 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]). Intrinsic stimuli were colored in one of these colors and encased by a white (255, 255, 255) frame. Extrinsic stimuli were white with a colored frame. All combinations of shapes and colors were implemented and used as stimuli; they were presented on a black (0, 0, 0) background. The shapes subtended a visual angle of $1.49^\circ \times 1.49^\circ$, and the surrounding frame subtended a visual angle of $3.54^\circ \times 3.54^\circ$. The width of the frame line 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 monitor with a resolution of $1,920 \times 1,080$ pixels at a refresh rate of 60 Hz. Participants were seated at an approximate viewing distance of 60 cm.

Figure 1

Example Stimuli



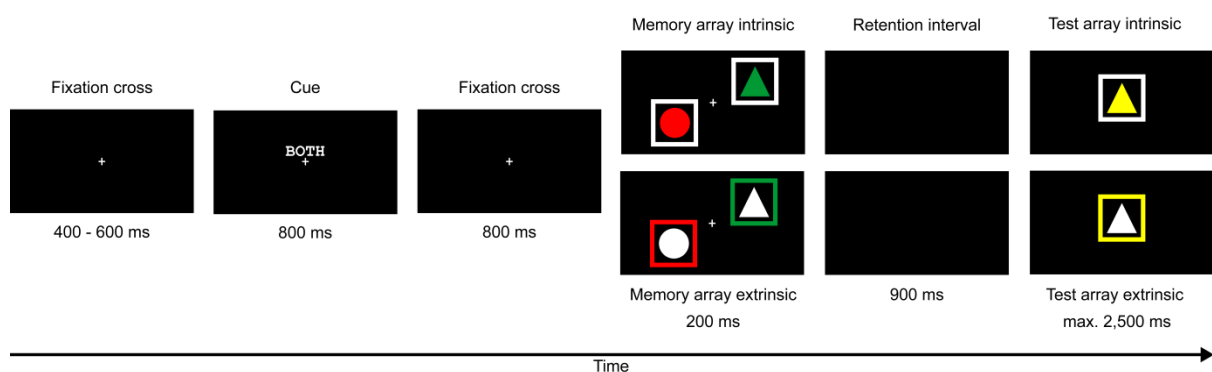
Note. Examples feature all nine geometrical shapes and seven colors used in the experiment. Top and bottom rows are examples of intrinsic stimuli; the middle row shows examples of extrinsic stimuli. See the online version of the paper for the color figure.

Procedure

The trial structure is illustrated in Figure 2. Each trial started with a central fixation cross, visible until the offset of the memory display. After 400-600 ms (with random jitter), a task cue was presented for 800 ms and then disappeared. In the shape-color condition, the cue was “BEID” (short for “Beides”, the German word for “both”), indicating that both shape and color information were task-relevant; in the shape-only condition, the cue was “FORM” (“shape”), indicating that only shape information was task-relevant. After an 800 ms post-cue interval, the study array was displayed for 200 ms. It comprised two stimuli, 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-fields of the circle. The two stimuli always differed in both color and shape. 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; Quinlan & Cohen, 2012; van Geldorp et al., 2015).

Figure 2

Schematic Illustration of the Trial Structure



Note. The example shows a color-change trial of the shape-color task, as indicated by the cue “BOTH” (translated for the figure; correct response is “new”). In the shape-only task, this would be a no-change trial as the color change would be task-irrelevant (correct response “old”). The figure is not drawn to scale.

In the shape-color task, participants decided whether or not the probe matched an item from the memory array in both shape and color. In the shape-only task, participants decided whether the probe matched a studied shape; color was irrelevant. From instructions and the practice phase, it was clear to participants that both features were relevant in the shape-color task, but that study-test change only ever involved one dimension (i.e., in change trials, the probe could differ from the study items in color or in shape, but never on both dimensions). Participant instructions are provided in the Supplement (available at <https://osf.io/pfbnz>). Responses were given on a Cedrus response pad (RB-834, Cedrus Corporation, San Pedro, California). The mapping of “match” and “mismatch” decisions to response hands was counterbalanced across participants. The test array was presented until a response was given or for a maximum of 2,500 ms; it was followed by a blank inter-trial interval of 1,500 ms. Both accuracy and response speed were emphasized.

There were a total of 640 trials; half of them belonged to the shape-color and shape-only tasks, respectively. In each task, half the trials used intrinsic and half extrinsic stimuli. In each test condition, half the trials required a match response and half a mismatch response. For a breakdown of trial numbers by condition, see Table 1; trial numbers were deemed acceptable based on guidelines from the literature (Duncan et al., 2009; Huffmeijer et al., 2014; Rietdijk et al., 2014) and given the need to balance this aspect against the total number of trials and associated fatigue concerns. To minimize task-switching costs, the task only changed after at least eight trials of the same task (i.e., shape-color vs. shape-only). To this end, for each task, trials were randomized, then subdivided into blocks of eight, and blocks of both tasks were presented in random order. Participants were able and encouraged to take a self-paced break every 80 trials. An additional 32 practice trials were not included in analyses. The experiment took approximately 75 minutes plus the time participants took for self-paced breaks to counter fatigue.

Table 1*Trial Types and Trial Numbers*

Task	Stimulus type	Change type	Correct Response	Trials (M_{incl})
Shape-color	Extrinsic	No change	Match	80 (64)
		Shape change (relev.)	Mismatch	40 (35)
		Color change (relev.)	Mismatch	40 (34)
	Intrinsic	No change	Match	80 (67)
		Shape change (relev.)	Mismatch	40 (34)
		Color change (relev.)	Mismatch	40 (35)
Shape-only	Extrinsic	No change	Match	40 (34)
		Shape Change (relev.)	Mismatch	80 (70)
	Intrinsic	Color change (irrelev.)	Match	40 (33)
		No change	Match	40 (33)
		Shape Change (relev.)	Mismatch	80 (70)
		Color change (irrelev.)	Match	40 (32)

Note. Incl, included in analysis; relev., task-relevant; irrelevant., task-irrelevant

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) were used, together with additional electrodes 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 k Ω . Signals

were amplified with a DC-coupled amplifier (Brain Amps, Brain Products, Munich, Germany) and recorded with a sampling rate of 1,000 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 as well as a high-pass filter at 0.1 Hz (24 dB/octave) and a low-pass filter at 30 Hz (12 dB/octave), as recommended by Luck (2014). The EEG signal was segmented into epochs from -200 ms to 800 ms, time-locked to the onset of the test display. Error and non-response trials were discarded; on average, this left between 32 and 35 trials per condition. Epochs were baseline corrected using the -200 to 0 ms interval. Ocular blink artifacts were corrected following 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 trials) were rejected before averaging based on 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: $\pm 100 \mu\text{V}$; 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), analyses of the N2 focused on the frontal electrode of the midline (Fz). To assess neural correlates of 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 150 to 250 ms post-stimulus-onset for the P2 (mean latency across conditions: $M = 185$ ms, $SD = 20$ ms) and negative maxima from 200 to 330 ms for the N2 (mean latency across conditions: $M = 246$ ms, $SD = 23$ ms). Differences between these peak amplitudes were computed for each condition and averaged across participants to quantify the N2 mismatch effect. Analysis of the FN400 old-

new effect focused on the time window from 350 to 400 ms post-probe onset—the time window in which Bledowski et al. (2012) had observed the effect of color changes. Because the FN400 often has a fronto-central distribution in WM studies (e.g., Bledowski et al., 2012; Ko et al., 2014), we based analysis on the average of Fz and Cz potentials.

Results

Data were analyzed in within-subjects ANOVAs; directed *t*-contrasts were used to test specific directed hypotheses. Data were analyzed separately for shape-color and shape-only tasks because color changes were associated with different responses (a new color called for a change response in the shape-color task but a no-change response in the shape-only task). Thus, in the shape-color task, a change-type (no change vs. color change) effect measures detection of color change (and the change type \times stimulus type interaction assesses color memory as a function of stimulus type). By contrast, in the shape-only task, we tested effects of interference caused by irrelevant color change; the change type effect here refers to the impact of color change on the detection of shape oldness. Data are available at <https://osf.io/pfbnz>.

Behavioral Data Analysis

Table 2 shows the mean accuracy scores and mean RTs for all conditions. For the analysis of response latencies, prior to behavioral data averaging, trials with RTs below 200 ms and inaccurate responses were excluded (7.33 % of trials), as were RTs exceeding 2.2-times the interquartile range above the third quartile of each participant's RT distribution (Hoaglin & Iglewicz, 1987; Hoaglin, Iglewicz, & Tukey, 1986; 2.66 % of remaining trials). RT analyses were based on log10-transformed RT data; for ease of comprehension, we report untransformed descriptive statistics; analyses with untransformed RT data yielded largely comparable results.

Table 2*Mean Accuracy and Response Times (RT, in ms; SDs in Parentheses) Across Conditions*

Task	Stimulus type	Change type	Accuracy	RT
Shape-color	Extrinsic	No change	.91 (.09)	635 (126)
		Color change	.94 (.06)	689 (139)
	Intrinsic	No change	.94 (.06)	635 (128)
		Color change	.96 (.05)	674 (165)
Shape-only	Extrinsic	No change	.95 (.06)	619 (118)
		Color change (irrelevant)	.90 (.06)	653 (144)
	Intrinsic	No change	.96 (.07)	615 (113)
		Color change (irrelevant)	.87 (.08)	682 (134)

Shape-Color Task

Accuracy. A 2 (stimulus type: intrinsic, extrinsic) \times 2 (change type: no change, color change) repeated measures ANOVA returned a main effect of stimulus type, $F(1, 23) = 18.93, p < .001, \eta_p^2 = .45$. Although generally high, memory was better for intrinsic ($M = .95, SE = .008$) than for extrinsic stimuli ($M = .92, SE = .011$), demonstrating an object advantage. There was no significant effect of change type, $F(1, 23) = 2.39, p = .136, \eta_p^2 = .09$,³ and no interaction, $F(1, 23) = 0.02, p = .894, \eta_p^2 < .001$.

RT. In a stimulus type \times change type ANOVA on RTs, the effect of stimulus type was non-significant, $F(1, 23) = 3.90, p = .060, \eta_p^2 = .14$, but there was a main effect of change type, $F(1, 23) = 19.06, p < .001, \eta_p^2 = .45$, with no-change decisions ($M = 635$ ms, $SE = 26$) faster than change decisions ($M = 682$ ms, $SE = 31$). There was also a significant

³ As pointed out by a reviewer, this may be a small effect not detected due to lack of power. While we are hesitant to draw strong conclusions, it may signal that a relevant color change is a salient change and thus sends a strong mismatch signal regardless of intrinsicity.

interaction, $F(1, 23) = 5.41, p = .029, \eta_p^2 = .19$, indicating that the RT cost of a relevant color change was slightly larger in the extrinsic compared to the intrinsic case.⁴

Shape-Only Task

Accuracy. A 2 (stimulus type) \times 2 (change type) ANOVA found no main effect of stimulus type, $F(1, 23) = 1.89, p = .182, \eta_p^2 = .08$. However, there was a main effect of change type, $F(1, 23) = 59.72, p < .001, \eta_p^2 = .72$, indicating better shape recognition in the no-change ($M = .95, SE = .011$) than the color-change condition ($M = .88, SE = .013$). The interaction was associated with $F(1, 23) = 3.68, p = .068, \eta_p^2 = .14$. As our hypothesis was directed, the appropriate test to assess whether the interference induced by the task-irrelevant color change was larger for intrinsic ($M = .09, SE = .015$) than for extrinsic stimuli ($M = .05, SE = .010$) is a directed test, which was significant, $t(23) = 1.92, p = .034, \text{Cohen's } d_z = .39$.⁵

RT. The corresponding stimulus type \times change type ANOVA on RTs yielded similar results: There was a significant main effect of stimulus type, $F(1, 23) = 6.41, p = .019, \eta_p^2 = .22$, with slightly faster responses to extrinsic ($M = 636 \text{ ms}; SE = 26$) compared to intrinsic items ($M = 649 \text{ ms}; SE = 25$),⁶ as well as an effect of change type, $F(1, 23) = 44.58, p < .001, \eta_p^2 = .66$, indicating that responses to old shapes were slower in the color-change condition ($M = 668 \text{ ms}, SE = 28$) than the no-change condition ($M = 617 \text{ ms}, SE = 23$). These main effects were qualified by the predicted interaction, $F(1, 23) = 11.66, p = .002, \eta_p^2 = .34$. Expressed as a directed test, the slowing caused by irrelevant color change was larger for intrinsic stimuli ($M = 66 \text{ ms}, SE = 10$) than for extrinsic stimuli ($M = 34 \text{ ms}, SE = 11$), $t(23) = 3.42, p = .002, d_z = .70$.

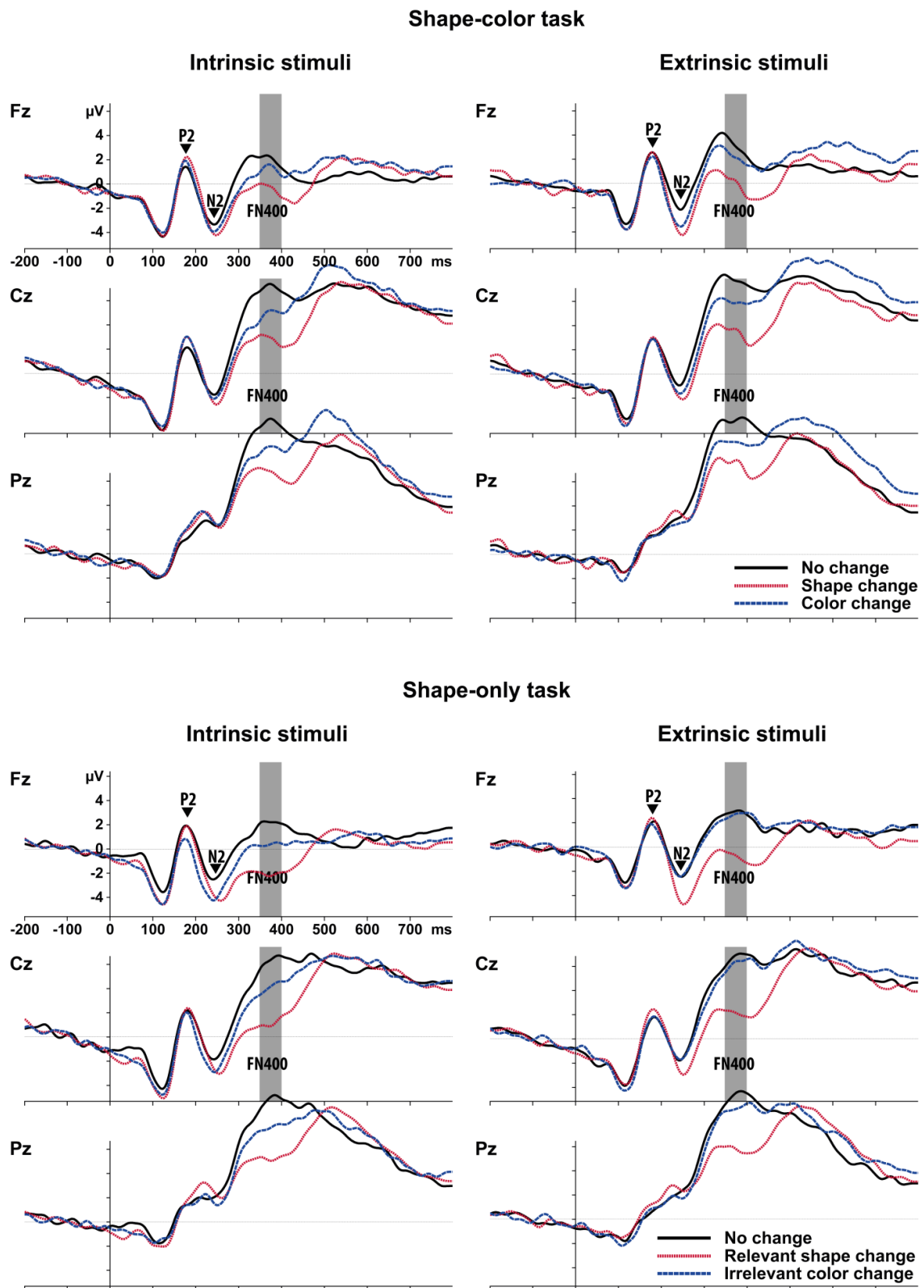
ERP Data Analysis

ERPs time-locked to the onset of the test probe are presented in Figure 3.

⁴ The interaction was non-significant in the analysis of untransformed RT.

⁵ Results were comparable with corrected recognition scores (correct-rejection rate – miss rate).

⁶ The main effect of stimulus type was non-significant in the analysis of untransformed RT.

Figure 3*Grand-Average Waveforms Across Conditions*

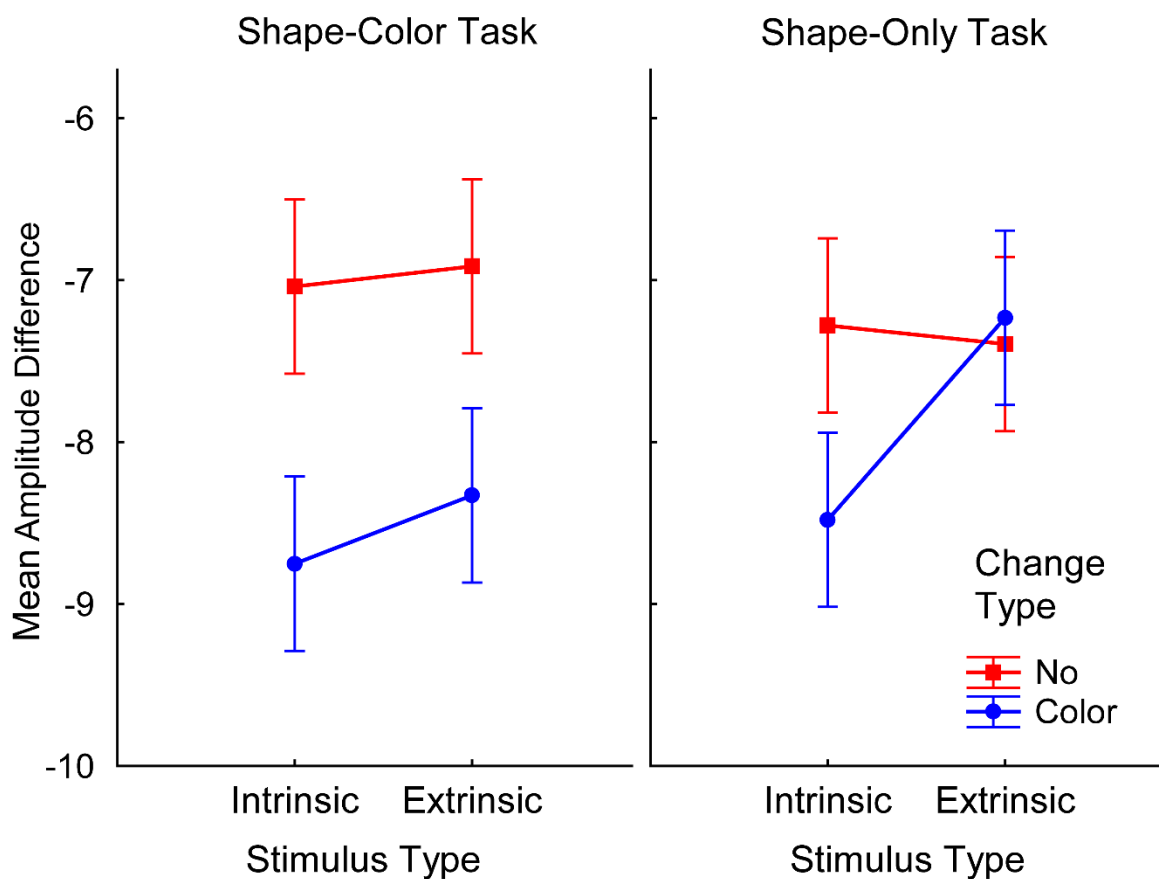
Note. Gray areas highlight the FN400 time window. For illustrational purposes, data were filtered with a 25 Hz high-cutoff filter (12 dB/Oct) following Luck (2014).

Shape-Color Task

N2. Figure 4 shows N2 effects across conditions. In the shape-color task, a 2 (stimulus type) \times 2 (change type) repeated measures ANOVA returned a main effect of change type, $F(1, 23) = 17.85, p < .001, \eta_p^2 = .44$, indicating that a color change elicited enhanced negativity ($M = -8.54 \mu\text{V}, SE = 1.02$) compared to the no-change condition ($M = -6.98 \mu\text{V}, SE = 0.90$) for both stimulus types. There was no significant main effect of stimulus type, $F(1, 23) = 1.15, p = .294, \eta_p^2 = .05$, nor an interaction, $F(1, 23) = 0.32, p = .578, \eta_p^2 = .01$.

Figure 4

Mean N2 Effects (in μV) Across Conditions

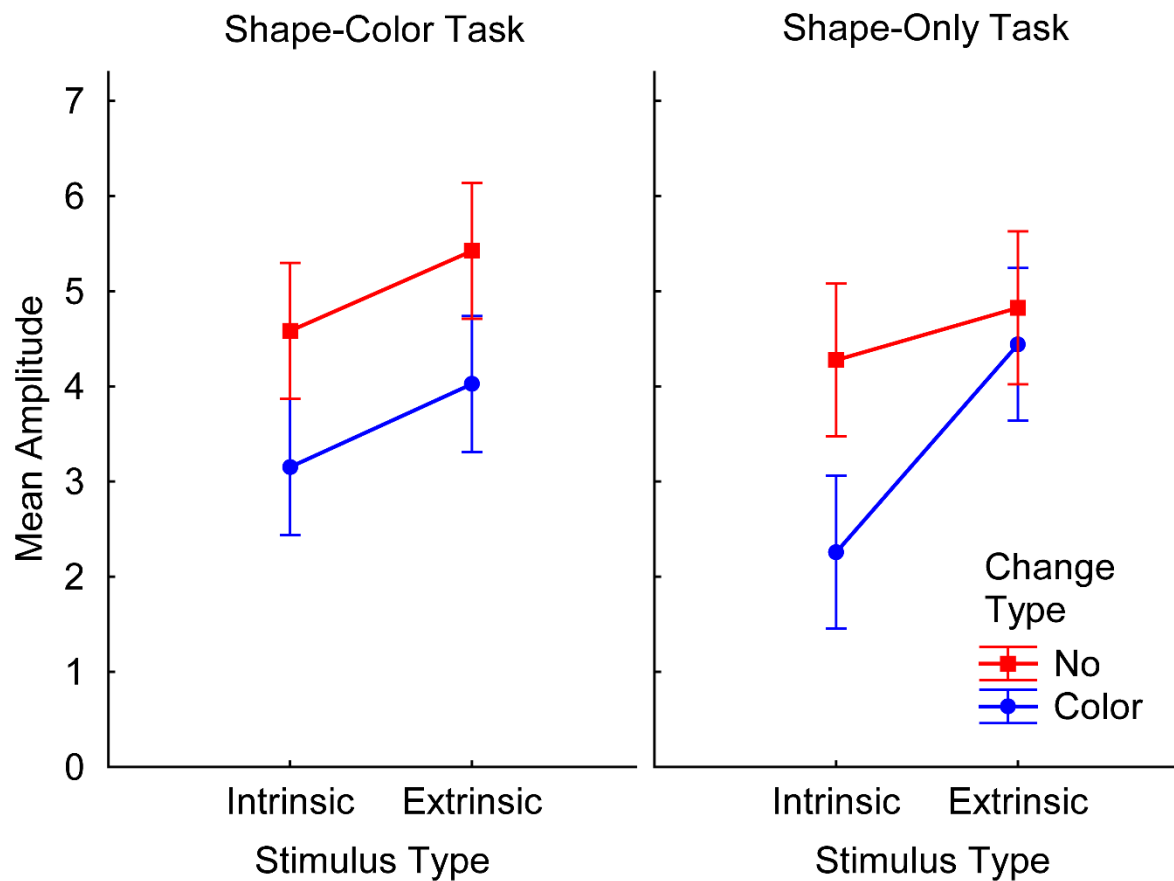


Note. Effects show peak-to-peak P2-N2 amplitude differences measured at Fz. Whiskers indicate 95% within-subject CIs (Jarmasz & Hollands, 2009).

FN400. FN400 data are illustrated in Figure 5. In the shape-color task, a 2×2 ANOVA again yielded a main effect of change type, $F(1, 23) = 9.93, p = .004, \eta_p^2 = .30$, with a more negative ERP for color-change trials ($M = 3.59 \mu\text{V}, SE = 1.16$) than no-change trials ($M = 5.00 \mu\text{V}, SE = 1.13$). Neither the main effect of stimulus type, $F(1, 23) = 3.94, p = .059, \eta_p^2 = .15$, nor the interaction, $F(1, 23) < 0.01, p = .965, \eta_p^2 < .01$, were significant.

Figure 5

Mean FN400 Amplitudes (in μV) Across Conditions



Note. Whiskers indicate 95% within-subject CIs (Jarmasz & Hollands, 2009).

Shape-Only Task

N2. In the shape-only task, the 2 (stimulus type) \times 2 (change type) ANOVA returned no main effect of stimulus type, $F(1, 23) = 1.55, p = .226, \eta_p^2 = .06$, no main effect of change type, $F(1, 23) = 2.85, p = .105, \eta_p^2 = .11$, but the predicted significant interaction,

$F(1, 23) = 6.94, p = .015, \eta_p^2 = .23$. A directed contrast confirmed that a color change had a larger effect for intrinsic ($\Delta_M = -1.20 \mu\text{V}, SE = 0.30$), than for extrinsic stimuli ($\Delta_M = 0.16 \mu\text{V}, SE = 0.49$), $t(23) = 2.63, p = .007, d_z = .54$.

FN400. In the shape-only condition, the 2×2 ANOVA yielded significant main effects of stimulus type, $F(1, 23) = 13.73, p = .001, \eta_p^2 = .37$, and change type, $F(1, 23) = 7.48, p = .012, \eta_p^2 = .25$, as well as the predicted significant interaction, $F(1, 23) = 4.44, p = .046, \eta_p^2 = .16$.⁷ Expressed as a directed contrast, color change had a larger effect for intrinsic ($\Delta_M = -2.02 \mu\text{V}, SE = 0.55$), than for extrinsic stimuli ($\Delta_M = -0.39 \mu\text{V}, SE = 0.62$), $t(23) = 2.11, p = .023, d_z = .43$.

Discussion

The aim of this study was to corroborate previous findings of a processing advantage of intrinsic over extrinsic object features in visual WM. 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, under the assumption that intrinsic processing advantages would arise from early object-integration processes rather than later decision-making processes. To the extent that intrinsic but not extrinsic object feature information is involuntarily integrated during perception, we expected ERP mismatch effects to be elicited by intrinsic color changes irrespective of task relevance. By contrast, we expected mismatch effects to be elicited by extrinsic color changes only if color was task-relevant.

⁷ As the FN400 analysis used an average ERP using two electrodes, we ran an ancillary analysis with electrode (Fz, Cz) as an additional factor. While there was a main effect of electrode, $F(1, 23) = 34.21, p < .001, \eta_p^2 = .60$, indicating that the FN400 was more positive at Cz than Fz, electrode did not moderate the critical interaction, $F(1, 23) = 0.04, p = .850, \eta_p^2 < .01$.

Overall, results supported these hypotheses: on a behavioral level, recognition of shape-color conjunctions was better for intrinsic compared to extrinsic stimuli. Moreover, task-irrelevant intrinsic color changes resulted in performance costs. Our investigation of early N2 mismatch effects and FN400-like old-new effects showed that only intrinsic task-irrelevant color changes 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 (also see Udale et al., 2017). In sum, the current study provided electrophysiological support for a processing advantage of intrinsic over extrinsic stimuli at the early stages of target processing.

Intentional Processing of Intrinsic and Extrinsic Features

In the shape-color task, both shape and color changes from study to test were task-relevant, and therefore color was arguably encoded into WM intentionally with both stimulus types. Behavioral recognition performance was overall better for intrinsic compared to extrinsic shape-color conjunctions, although performance differences were rather small. Since intrinsic and extrinsic stimuli were structurally equivalent, the change-detection advantage for intrinsic color resembles previous findings of an object-based processing benefit: it is easier to attend to multiple features that are integrated within the object outline than to disjunct features (e.g., Xu, 2002a, 2002c).

In the ERP data, color changes evoked mismatch signals. Intrinsic and extrinsic color information influenced the early stages of target evaluation to a similar extent, with comparable N2 mismatch effects and FN400 modulations for intrinsic and extrinsic color changes. The comparable intrinsic and extrinsic mismatch effects suggest that both intrinsic and extrinsic features are integrated into the WM representation used to evaluate the test probe, thus contributing to mismatch detection, if they are task-relevant. This is in contrast to long-term memory research, where extrinsic information typically does not influence earlier

components of the recognition process (see Zimmer & Ecker, 2010). In WM, however, extrinsic information can apparently influence earlier stages of target processing, potentially through a more top-down process, as will be discussed below.

Obligatory Processing of Intrinsic and Extrinsic Features

In the shape-only task, the task did not require the intentional processing of color information. In this case, behavioral performance costs caused by task-irrelevant color change were greater for intrinsic compared to extrinsic stimuli. These behavioral results replicate findings from previous studies, highlighting the importance of stimulus type for WM processing (e.g., Ecker et al., 2013).

There was a striking difference in ERPs for intrinsic and extrinsic conditions. For intrinsic stimuli, irrelevant color changes elicited an N2 signal similar to the one elicited by relevant shape changes. By contrast, the N2 in the extrinsic color-change condition resembled the no-change condition. 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 observed pattern for the FN400-like old-new effect was similar, with a clear effect in the intrinsic condition but no difference between no-change and irrelevant-color-change conditions with extrinsic stimuli. In sum, the N2 and FN400 findings support our hypothesis that intrinsic but not extrinsic information is an obligatory part of the WM representation used to perform change detection.

The fact that there were no early ERP differences between no-change and extrinsic color-change conditions despite significant behavioral costs associated with irrelevant extrinsic color change suggests that behavioral responses were also influenced by later decision making processes (see Hyun et al., 2009).

Limitations and Future Directions

A limitation of this study is that we cannot rule out an alternative explanation of the object advantage in terms of differential spatial attention. We note that the experiment was not designed to elucidate the relevance of attention for feature processing (e.g., Treisman, 2006) or integration of multiple features (e.g., Hitch et al., 2020; Zhou et al., 2021). Participants always knew the to-be-performed task in advance and the task cue was always valid; it is therefore possible that participants used the cue in the shape-only task to focus spatial attention exclusively on the shape and to narrow the spatial “spotlight” to the size of the shape. Due to the adaptation of exogenous attention, intrinsic color would always be in the spotlight, extrinsic color outside of it. Such an adjusted window of attention could block the extrinsic but not the intrinsic color information from entering working memory at study or test.

We believe this is unlikely, given the spatial proximity of the colored frame (Xu, 2006; also see Nishina et al., 2007) and the fact that exogenous cues can overpower endogenous attempts to control spatial attention (e.g., Shipstead et al., 2012). Moreover, at study, stimuli were presented at random locations, and the short presentation time made precise attentional shifts or tuning all but impossible. At test, however, the attentional spotlight may have been narrowed to the target shape (Cobos & Chica, 2022; also see Heitz & Engle, 2007), and the extrinsic frame may have thus been outside of the focus of attention. It is therefore possible that the observed effect of intrinsicity was due to the presence of the irrelevant feature within either the boundary of the attended object or the attentional spotlight. In Ecker et al. (2013) we provided evidence that the object matters and not the spotlight, but the present experiment cannot shed additional light on this question. However, other studies have shown that task-irrelevant context features can be encoded into visual WM (e.g., Hu et al., 2014) and that participants tend to memorize task-irrelevant proximal context features at

levels significantly above chance (e.g., Huang & Watanabe, 2012). Hence, external features can be integrated into WM, but intrinsicity nevertheless matters (i.e., whether a feature is located within or outside of an object's boundary). Additional support for the relevance of object boundaries for WM comes from the observation that a change in the topological structure of an item—a so-called non-homeomorphic change that alters the structure of the object—has a stronger influence on WM performance than a (homeomorphic) change of the item's shape (Wei et al., 2019).⁸

Future research could further investigate the importance of spatial attention or of object boundaries for feature selection, for example by varying the size of the stimuli to make it more difficult to tune the attentional system, or via an experiment where the irrelevant context color is changed within the same spotlight as the relevant shape (e.g., a shape-memory task in which the target shape is partially occluded by a foreground shape, where irrelevant shape-color changes should only produce performance costs if they relate to the target shape not the distractor shape in the foreground). For now, it remains a possibility that the differences between intrinsic and extrinsic binding that we have observed are indeed driven by differences in attention (also see Ecker et al., 2007c). We also acknowledge that the integration of intrinsic features may not be an all-or-none process, as it may be possible to flexibly prioritize/deprioritize individual feature dimensions in visual WM (e.g., Hajonides et al., 2020; Niklaus et al., 2017; Park et al., 2017). Finally, sample size in this study was comparatively small, and power was further reduced by exclusion of two participants (achieved power was 77% for $d_z = 0.50$); true effects in the population might be smaller than we assumed, and thus future experiments should replicate with larger samples (see Brysbaert, 2019).

⁸ To illustrate, changing a solid square to a solid disc is a homeomorphic shape change, whereas changing a solid square to a hollow square is an example of a non-homeomorphic topological change.

Concluding Remarks

The present study provides additional evidence that intrinsic but not extrinsic feature information is obligatorily processed in WM (also see Udale et al., 2017). We argue that modulation of the focus of attention (see Oberauer, 2002) is of major importance for the observed processing differences between intrinsic and extrinsic information. Under indirect test conditions (i.e., the shape-only task), attentional selection was always directed to the shape in a stimulus-driven manner; consequentially, intrinsic information was able to contribute to evaluative processes, whereas no such influence was found for extrinsic information because in this case it was part of a non-selected object. In order for extrinsic information to influence stimulus evaluation, an intentional orientation toward the spatially-disjunct extrinsic information was necessary (in the shape-color task). Intrinsic information might thus experience a processing advantage in the competition for representation as soon as the object is attended (see, e.g., Boynton, 2005; Hilimire et al., 2010). This view therefore suggests that the object advantage in WM is in part modulated by attentional control processes, such that intrinsic feature information influences stimulus evaluation irrespective of attentional resources being targeted specifically at the feature, whereas extrinsic feature information only contributes to the evaluation if the task demands it and attention is deployed accordingly. Thus, top-down adjustments of the focus of attention could be of critical importance for the observed processing difference between intrinsic and extrinsic information during feature integration. In other words, both the modulation of the focus of attention by the perceptual structure of a stimulus (bottom-up) and task demands (top-down) matter, but the latter can overwrite the stimulus-driven organization. Our findings are thus more in line with a general view of WM as a task-oriented network that interacts closely with perception and attention rather than a time-oriented storage buffer (Gao et al., 2011; Zimmer, 2008).

References

- Adam, K. C. S., Vogel, E. K., & Awh, E. (2017). Clear evidence for item limits in visual working memory. *Cognitive Psychology*, *97*, 79–97.
<https://doi.org/10.1016/j.cogpsych.2017.07.001>
- Bays, P. M., Catalao, R. F. G., & Husain, M. (2009). The precision of visual working memory is set by allocation of a shared resource. *Journal of Vision*, *9*(10), 7.
<https://doi.org/10.1167/9.10.7>
- Bays, P. M., Wu, E. Y., & Husain, M. (2011). Storage and binding of object features in visual working memory. *Neuropsychologia*, *49*(6), 1622–1631.
<https://doi.org/10.1016/j.neuropsychologia.2010.12.023>
- Bledowski, C., Kaiser, J., Wibral, M., Yildiz-Erzberger, K., & Rahm, B. (2012). Separable neural bases for subprocesses of recognition in working memory. *Cerebral Cortex*, *22*(8), 1950–1958. <https://doi.org/10.1093/cercor/bhr276>
- Boduroglu, A., & Shah, P. (2009). Effects of spatial configurations on visual change detection: An account of bias changes. *Memory & Cognition*, *37*(8), 1120–1131.
<https://doi.org/10.3758/MC.37.8.1120>
- Boynton, G. M. (2005). Attention and visual perception. *Current Opinion in Neurobiology*, *15*(4), 465–469. <https://doi.org/10.1016/j.conb.2005.06.009>
- Brady, T. F., Konkle, T., & Alvarez, G. A. (2011). A review of visual memory capacity: Beyond individual items and toward structured representations. *Journal of Vision*, *11*(5), 4. <https://doi.org/10.1167/11.5.4>
- Brown, L. A., & Brockmole, J. R. (2010). The role of attention in binding visual features in working memory: Evidence from cognitive ageing. *Quarterly Journal of Experimental Psychology*, *63*(10), 2067–2079.
<https://doi.org/10.1080/17470211003721675>

- Brysbaert, M. (2019). How many participants do we have to include in properly powered experiments? A tutorial of power analysis with reference tables. *Journal of Cognition*, 2(1), 16. <https://doi.org/10.5334/joc.72>
- Ceraso, J. (1985). Unit formation in perception and memory. In G. H. Bower (Ed.), *The Psychology of Learning and Motivation: Advances in Research and Theory* (Vol. 19, pp. 179–210). Academic Press. [https://doi.org/10.1016/S0079-7421\(08\)60527-7](https://doi.org/10.1016/S0079-7421(08)60527-7)
- Cobos, M. I., & Chica, A. B. (2022). Attention does not always help: The role of expectancy, divided, and spatial attention on illusory conjunctions. *Quarterly Journal of Experimental Psychology*. <https://doi.org/10.1177/17470218221089625>
- Cui, L., Wang, Y., Wang, H., Tian, S., & Kong, J. (2000). Human brain sub-systems for discrimination of visual shapes. *NeuroReport*, 11(11), 2415–2418. <https://doi.org/10.1097/00001756-200008030-00015>
- Davachi, L. (2006). Item, context and relational episodic encoding in humans. *Current Opinion in Neurobiology*, 16(6), 693–700. <https://doi.org/10.1016/j.conb.2006.10.012>
- Delvenne, J.-F., & Bruyer, R. (2004). Does visual short-term memory store bound features? *Visual Cognition*, 11(1), 1–27. <https://doi.org/10.1080/13506280344000167>
- Duncan, C. C., Barry, R. J., Connolly, J. F., Fischer, C., Michie, P. T., Näätänen, R., ... Van Petten, C. (2009). Event-related potentials in clinical research: Guidelines for eliciting, recording, and quantifying mismatch negativity, P300, and N400. *Clinical Neurophysiology*, 120(11), 1883–1908.
- Ecker, U. K. H., Maybery, M. T., & Zimmer, H. D. (2013). Binding of intrinsic and extrinsic features in working memory. *Journal of Experimental Psychology: General*, 142(1), 218–234. <https://doi.org/10.1037/a0028732>

- Ecker, U. K. H., Zimmer, H. D., & Groh-Bordin, C. (2007a). Color and context: An ERP study on intrinsic and extrinsic feature binding in episodic memory. *Memory & Cognition*, *35*(6), 1483–1501. <https://doi.org/10.3758/BF03193618>
- Ecker, U. K. H., Zimmer, H. D., & Groh-Bordin, C. (2007b). The influence of object and background color manipulations on the electrophysiological indices of recognition memory. *Brain Research*, *1185*, 221–230. <https://doi.org/10.1016/j.brainres.2007.09.047>
- Ecker, U. K. H., Zimmer, H. D., Groh-Bordin, C., & Mecklinger, A. (2007c). Context effects on familiarity are familiarity effects of context—An electrophysiological study. *International Journal of Psychophysiology*, *64*, 146–156. <https://doi.org/10.1016/j.ijpsycho.2007.01.005>
- Emrich, S., & Ferber, S. (2012). Competition increases binding errors in visual working memory. *Journal of Vision*, *12*(4), 12. <https://doi.org/10.1167/12.4.12>
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*, 175–191. <https://doi.org/10.3758/BF03193146>
- Folstein, J. R., & van Petten, C. (2008). Influence of cognitive control and mismatch on the N2 component of the ERP: A review. *Psychophysiology*, *45*(1), 152–170. <https://doi.org/10.1111/j.1469-8986.2007.00602.x>
- Fougnie, D., & Alvarez, G. A. (2011). Object features fail independently in visual working memory: Evidence for a probabilistic feature-store model. *Journal of Vision*, *11*(12), 3. <https://doi.org/10.1167/11.12.3>
- Fougnie, D., Asplund, C. L., & Marois, R. (2010). What are the units of storage in visual working memory? *Journal of Vision*, *10*(12), 27. <https://doi.org/10.1167/10.12.27>

- Frings, C., & Rothermund, K. (2017). How perception guides action: Figure-ground segmentation modulates integration of context features into S-R episodes. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(11), 1720-1729. doi:10.1037/xlm0000403
- Gajewski, D. A., & Brockmole, J. R. (2006). Feature bindings endure without attention: Evidence from an explicit recall task. *Psychonomic Bulletin & Review*, *13*(4), 581–587. <https://doi.org/10.3758/BF03193966>
- Gao, T., Gao, Z., Li, J., Sun, Z., & Shen, M. (2011). The perceptual root of object-based storage: An interactive model of perception and visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(6), 1803–1823. <https://doi.org/10.1037/a0025637>
- Gao, Z., Li, J., Yin, J., & Shen, M. (2010). Dissociated mechanisms of extracting perceptual information into visual working memory. *PLOS ONE*, *5*(12), e14273. <https://doi.org/10.1371/journal.pone.0014273>
- Garner, W. R. (1974). *The processing of information and structure. The experimental psychology series*. Erlbaum.
- Gehring, W. J., Gratton, G., Coles, M. G. H., & Donchin, E. (1992). Probability effects on stimulus evaluation and response processes. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(1), 198–216. <https://doi.org/10.1037//0096-1523.18.1.198>
- Gratton, G., Coles, M. G. H., & Donchin, E. (1983). A new method for off-line removal of ocular artifact. *Electroencephalography and Clinical Neurophysiology*, *55*(4), 468–484. [https://doi.org/10.1016/0013-4694\(83\)90135-9](https://doi.org/10.1016/0013-4694(83)90135-9)

- Gu, Q., Dai, A., Ye, T., Huang, B., Lu, X., Shen, M., & Gao, Z. (2022). Object-based encoding in visual working memory: A critical revisit. *Quarterly Journal of Experimental Psychology*, 75(8), 1397-1410.
- Hajonides, J. E., van Ede, F., Stokes, M. G., & Nobre, A. C. (2020). Comparing the prioritization of items and feature-dimensions in visual working memory. *Journal of Vision*, 20(8), 25. <https://doi.org/10.1167/jov.20.8.25>
- Heitz, R. P., & Engle, R. W. (2007). Focusing the spotlight: Individual differences in visual attention control. *Journal of Experimental Psychology: General*, 136(2), 217-240. <https://doi.org/10.1037/0096-3445.136.2.217>
- Hilimire, M. R., Mounts, J. R. W., Parks, N. A., & Corballis, P. M. (2010). Event-related potentials dissociate effects of salience and space in biased competition for visual representation. *PLOS ONE*, 5(9), e12677. <https://doi.org/10.1371/journal.pone.0012677>
- Hitch, G. J., Allen, R. J., & Baddeley, A. D. (2020). Attention and binding in visual working memory: Two forms of attention and two kinds of buffer storage. *Attention, Perception, & Psychophysics*, 82, 280-293. <https://doi.org/10.3758/s13414-019-01837-x>
- Hoaglin, D. C., & Iglewicz, B. (1987). Fine-tuning some resistant rules for outlier labeling. *Journal of the American Statistical Association*, 82(400), 1147–1149. <https://doi.org/10.2307/2289392>
- Hoaglin, D. C., Iglewicz, B., & Tukey, J. W. (1986). Performance of some resistant rules for outlier labeling. *Journal of the American Statistical Association*, 81(396), 991–999. <https://doi.org/10.2307/2289073>

- Hu, Y., Hitch, G. J., Baddeley, A. D., Zhang, M., & Allen, R. J. (2014). Executive and perceptual attention play different roles in visual working memory: Evidence from suffix and strategy effects. *Journal of Experimental Psychology: Human Perception and Performance*, *40*, 1665–1678. <https://doi.org/10.1037/a0037163>
- Huang, T.-R., & Watanabe, T. (2012). Task attention facilitates learning of task-irrelevant stimuli. *PLOS ONE*, *7*(4), e35946. <https://doi.org/10.1371/journal.pone.0035946>
- Huffmeijer, R., Bakermans-Kranenburg, M. J., Alink, L. R., & van IJzendoorn, M. H. (2014). Reliability of event-related potentials: The influence of number of trials and electrodes. *Physiology & Behavior*, *130*, 13–22.
- Hyun, J.-S., Woodman, G. F., Vogel, E. K., Hollingworth, A. R., & Luck, S. J. (2009). The comparison of visual working memory representations with perceptual inputs. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(4), 1140–1160. <https://doi.org/10.1037/a0015019>
- Jarmasz, J., & Hollands, J. G. (2009). Confidence intervals in repeated-measures designs: The number of observations principle. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, *63*(2), 124–138. <https://doi.org/10.1037/a0014164>
- 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>
- Ko, P. C., Duda, B., Hussey, E., Mason, E., Molitor, R. J., Woodman, G. F., & Ally, B. A. (2014). Understanding age-related reductions in visual working memory capacity: examining the stages of change detection. *Attention, Perception, & Psychophysics*, *76*(7), 2015–2030. <https://doi.org/10.3758/s13414-013-0585-z>

- Kong, J., Wang, Y., Zhang, W., Wang, H., Wei, H., Shang, H., . . . Zhuang, D. (2000). Event-related brain potentials elicited by a number discrimination task. *NeuroReport*, *11*(6), 1195–1197. <https://doi.org/10.1097/00001756-200004270-00010>
- Logie, R. H., Brockmole, J. R., & Jaswal, S. (2011). Feature binding in visual short-term memory is unaffected by task-irrelevant changes of location, shape, and color. *Memory & Cognition*, *39*(1), 24–36.
- Logie, R. H., Camos, V., & Cowan, N. (Eds.) (2021). *Working memory: State of the science*. Oxford University Press.
- Liotti, M., Woldorff, M. G., Perez, R., & Mayberg, H. S. (2000). An ERP study of the temporal course of the Stroop color-word interference effect. *Neuropsychologia*, *38*(5), 701–711. [https://doi.org/10.1016/S0028-3932\(99\)00106-2](https://doi.org/10.1016/S0028-3932(99)00106-2)
- Luck, S. J. (2014). *An introduction to the event-related potential technique* (2. ed.). MIT Press.
- Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–281. <https://doi.org/10.1038/36846>
- Ma, W. J., Husain, M., & Bays, P. M. (2014). Changing concepts of working memory. *Nature Neuroscience*, *17*(3), 347–356. <https://doi.org/10.1038/nn.3655>
- Mance, I., & Vogel, E. K. (2013). Visual working memory. *WIREs Cognitive Science*, *4*(2), 179–190. <https://doi.org/10.1002/wcs.1219>
- Mao, W., & Wang, Y. (2008). The active inhibition for the processing of visual irrelevant conflict information. *International Journal of Psychophysiology*, *67*(1), 47–53. <https://doi.org/10.1016/j.ijpsycho.2007.10.003>
- Mecklinger, A., & Bader, R. (2020). From fluency to recognition decisions: A broader view of familiarity-based remembering. *Neuropsychologia*, *146*, 107527. <https://doi.org/10.1016/j.neuropsychologia.2020.107527>

- Niklaus, M., Nobre, A. C., & van Ede, F. (2017). Feature-based attentional weighting and spreading in visual working memory. *Scientific Reports*, 7(1), 1-10.
<https://doi.org/10.1038/srep42384>
- Nishina, S., Seitz, A. R., Kawato, M., Watanabe, T. (2007). Effect of spatial distance to the task stimulus on task-irrelevant perceptual learning of static Gabors. *Journal of Vision*, 7(13), 2. <https://doi.org/10.1167/7.13.2>
- Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28(3), 411–421. <https://doi.org/10.1037/0278-7393.28.3.411>
- Oberauer, K. (2021). Little support for discrete item limits in visual working memory. *Psychological Science*. <https://doi.org/10.1177/09567976211068045>
- Park, Y. E., Sy, J. L., Hong, S. W., & Tong, F. (2017). Reprioritization of features of multidimensional objects stored in visual working memory. *Psychological Science*, 28, 1773-1785. <https://doi.org/10.1177/0956797617719949>
- Quinlan, P. T., & Cohen, D. J. (2012). Grouping and binding in visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 38(5), 1432–1438. <https://doi.org/10.1037/a0027866>
- Randall, W. M., & Smith, J. L. (2011). Conflict and inhibition in the cued-Go/NoGo task. *Clinical Neurophysiology*, 122(12), 2400–2407.
<https://doi.org/10.1016/j.clinph.2011.05.012>
- Rietdijk, W. J., Franken, I. H., & Thurik, A. R. (2014). Internal consistency of event-related potentials associated with cognitive control: N2/P3 and ERN/Pe. *PLOS ONE*, 9(7), e102672
- Rugg, M. D., & Curran, T. (2007). Event-related potentials and recognition memory. *Trends in Cognitive Sciences*, 11(6), 251–257. <https://doi.org/10.1016/j.tics.2007.04.004>

- Saiki, J. (2016). Location-unbound color-shape binding representations in visual working memory. *Psychological Science*, 27(2), 178–190.
<https://doi.org/10.1177/0956797615616797>
- Schmalbrock, P., & Frings, C. (2022). A mighty tool not only in perception: Figure-ground mechanisms control binding and retrieval alike. *Attention, Perception, & Psychophysics*, 84(7), 2255-2270. doi:10.3758/s13414-022-02511-5
- Schneegans, S., Taylor, R., & Bays, P. M. (2020). Stochastic sampling provides a unifying account of visual working memory limits. *Proceedings of the National Academy of Sciences of the USA*, 117(34), 20959-20968. doi:10.1073/pnas.2004306117
- Serences, J. T., Ester, E. F., Vogel, E. K., & Awh, E. (2009). Stimulus-specific delay activity in human primary visual cortex. *Psychological science*, 20(2), 207-214.
- Shen, M., Tang, N., Wu, F., Shui, R., & Gao, Z. (2013). Robust object-based encoding in visual working memory. *Journal of Vision*, 13(2), 1.
- Shin, H., & Ma, W. J. (2016). Crowdsourced single-trial probes of visual working memory for irrelevant features. *Journal of Vision*, 16(5), 10.
- Shipstead, Z., Harrison, T. L., & Engle, R. W. (2012). Working memory capacity and visual attention: Top-down and bottom-up guidance. *Quarterly Journal of Experimental Psychology*, 65(3), 401-407. <https://doi.org/10.1080/17470218.2012.655698>
- Staresina, B. P., & Davachi, L. (2009). Mind the gap: Binding experiences across space and time in the human hippocampus. *Neuron*, 63(2), 267–276.
<https://doi.org/10.1016/j.neuron.2009.06.024>
- Swan, G., Collins, J., & Wyble, B. (2016). Memory for a single object has differently variable precisions for relevant and irrelevant features. *Journal of Vision*, 16(3), 32.

- Tam, J., & Wyble, B. (2022). Location has a privilege, but it is limited: Evidence from probing task-irrelevant location. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. <https://doi.org/10.1037/xlm0001147>
- Tian, S., Wang, Y., & Wang, H. (2001). Interstimulus interval effect on event-related potential N270 in a color matching task. *Clinical Electroencephalography*, 32(2), 82–86. <https://doi.org/10.1177/155005940103200207>
- Treisman, A. (2006). How the deployment of attention determines what we see. *Visual Cognition*, 14(4-8), 411-443. doi:10.1080/13506280500195250
- Troyer, A. K., & Craik, F. I. M. (2000). The effect of divided attention on memory for items and their context. *Canadian Journal of Experimental Psychology/Revue Canadienne de Psychologie Expérimentale*, 54(3), 161–171. <https://doi.org/10.1037/h0087338>
- Udale, R., Farrell, S. & Kent, C. (2017). No evidence for binding of items to task-irrelevant backgrounds in visual working memory. *Memory & Cognition*, 45, 1144–1159. <https://doi.org/10.3758/s13421-017-0727-y>
- Van Geldorp, B., Parra, M. A., & Kessels, R. P. C. (2015). Cognitive and neuropsychological underpinnings of relational and conjunctive working memory binding across age. *Memory*, 23(8), 1112–1122. <https://doi.org/10.1080/09658211.2014.953959>
- Vidal, J. R., Gauchou, H. L., Tallon-Baudry, C., & O'Regan, J. K. (2005). Relational information in visual short-term memory: The structural gist. *Journal of Vision*, 5(3), 8. <https://doi.org/10.1167/5.3.8>
- Vul, E., Rieth, C. A., Lew, T. F., & Rich, A. N. (2020). The structure of illusory conjunctions reveals hierarchical binding of multipart objects. *Attention, Perception, & Psychophysics*, 82(2), 550-563. doi:10.3758/s13414-019-01867-5

- Wang, B., Cao, X., Theeuwes, J., Olivers, C. N., & Wang, Z. (2017). Separate capacities for storing different features in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *43*(2), 226-236.
- Wang, Y., Cui, L., Wang, H., Tian, S., & Zhang, X. (2004). The sequential processing of visual feature conjunction mismatches in the human brain. *Psychophysiology*, *41*(1), 21–29. <https://doi.org/10.1111/j.1469-8986.2003.00134.x>
- Wang, Y., Tian, S., Wang, H., Cui, L., Zhang, Y., & Zhang, X. (2003). Event-related potentials evoked by multi-feature conflict under different attentive conditions. *Experimental Brain Research*, *148*(4), 451–457. <https://doi.org/10.1007/s00221-002-1319-y>
- Wei, N., Zhou, T., Zhang, Z., Zhuo, Y., & Chen, L. (2019). *Journal of Vision*, *19*(7), 12. <https://doi.org/10.1167/19.7.12>
- West, R., & Alain, C. (1999). Event-related neural activity associated with the Stroop task. *Cognitive Brain Research*, *8*(2), 157–164. [https://doi.org/10.1016/S0926-6410\(99\)00017-8](https://doi.org/10.1016/S0926-6410(99)00017-8)
- Wilken, P., & Ma, W. J. (2004). A detection theory account of change detection. *Journal of Vision*, *4*(12), 11. <https://doi.org/10.1167/4.12.11>
- Xu, Y. (2002a). Encoding color and shape from different parts of an object in visual short-term memory. *Perception & Psychophysics*, *64*(8), 1260–1280. <https://doi.org/10.3758/BF03194770>
- Xu, Y. (2002b). Feature integration across parts in visual search. *Perception*, *31*(11), 1335–1347. <https://doi.org/10.1068/p3431>
- Xu, Y. (2002c). Limitations of object-based feature encoding in visual short-term memory. *Journal of Experimental Psychology: Human Perception and Performance*, *28*(2), 458–468. <https://doi.org/10.1037//0096-1523.28.2.458>

- Xu, Y. (2006). Understanding the object benefit in visual short-term memory: The roles of feature proximity and connectedness. *Perception & Psychophysics*, *68*(5), 815–828. <https://doi.org/10.3758/BF03193704>
- Xu, Y. (2010). The neural fate of task-irrelevant features in object-based processing. *Journal of Neuroscience*, *30*(42), 14020-14028.
- Yeung, N., Botvinick, M. M., & Cohen, J. D. (2004). The neural basis of error detection: Conflict monitoring and the error-related negativity. *Psychological Review*, *111*(4), 931–959. <https://doi.org/10.1037/0033-295X.111.4.931>
- Yin, J., Gao, Z., Jin, X., Ye, L., Shen, M., & Shui, R. (2011). Tracking the mismatch information in visual short term memory: An event-related potential study. *Neuroscience Letters*, *491*(1), 26–30. <https://doi.org/10.1016/j.neulet.2011.01.001>
- Zhang, Q., Shen, M., Tang, N., Zhao, G., & Gao, Z. (2013). Object-based encoding in visual working memory: A life span study. *Journal of Vision*, *13*(10), 11.
- Zhou, Y., Wu, F., Wan, X., Shen, M., & Gao, Z. (2021). Does the presence of more features in a bound representation in working memory require extra object-based attention? *Memory & Cognition*, *49*(8), 1583-1599. doi:10.3758/s13421-021-01183-0
- Zhou, J., Yin, J., Chen, T., Ding, X., Gao, Z., & Shen, M. (2011). Visual working memory capacity does not modulate the feature-based information filtering in visual working memory. *PLOS ONE*, *6*(9), e23873. <https://doi.org/10.1371/journal.pone.0023873>
- Zimmer, H. D. (2008). Visual and spatial working memory: From boxes to networks. *Neuroscience & Biobehavioral Reviews*, *32*(8), 1373–1395. <https://doi.org/10.1016/j.neubiorev.2008.05.016>

- Zimmer, H. D., & Ecker, U. K. H. (2010). Remembering perceptual features unequally bound in object and episodic tokens: Neural mechanisms and their electrophysiological correlates. *Neuroscience & Biobehavioral Reviews*, *34*(7), 1066–1079.
<https://doi.org/10.1016/j.neubiorev.2010.01.014>
- Zimmer, H. D., Mecklinger, A., & Lindenberger, U. (2006). Levels of binding: Types, mechanisms, and functions of binding in remembering. In H. D. Zimmer, A. Mecklinger, & U. Lindenberger (Eds.), *Handbook of binding and memory: Perspectives from cognitive neuroscience* (pp. 3–22). Oxford University Press.
- Zimmer, H. D., & Steiner, A. (2003). Colour specificity in episodic and in perceptual object recognition with enhanced colour impact. *European Journal of Cognitive Psychology*, *15*(3), 349–370. <https://doi.org/10.1080/09541440303603>

Acknowledgements: This research was conducted in the International Research Training Group “Adaptive Minds”, supported by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG) under Grant IRTG 1457. The research formed part of the first author’s PhD thesis at Saarland University.

Author contributions: AK and HDZ conceptualized the study and developed the analysis plan, with input from UKHE; AK conducted the experiment, and performed the analyses, under HDZ’s supervision. AK wrote an initial manuscript draft, HDZ and UKHE contributed substantially to the write-up. UKHE led the revisions.

Disclosure statement: The authors report no conflict of interest.