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Binding of intrinsic and extrinsic features in working memory

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Abstract

There is ongoing debate concerning the mechanisms of feature binding in working memory. In particular, there is controversy regarding the extent to which these binding processes are automatic. The present paper demonstrates that binding mechanisms differ depending on whether or not the to-be-integrated features are perceived as forming a coherent object. We presented a series of experiments that investigated the binding of color and shape, whereby color was either an intrinsic feature of the shape or an extrinsic feature of the shape's background. Results show that intrinsic color affected shape recognition even when it was incidentally studied and irrelevant for the recognition task. In contrast, extrinsic color did not affect shape recognition, even when the association of color and shape was encoded and retrievable on demand. This strongly suggests that binding of intrinsic intra-item information but not extrinsic contextual information is obligatory in visual working memory. We highlight links to perception as well as implicit and explicit long-term memory, which suggest that the intrinsic-extrinsic dimension is a principle relevant to multiple domains of human cognition.

Keywords: Feature binding; Working memory; Object representation

Binding of intrinsic and extrinsic features in working memory

Visual working memory (VWM) serves to hold visual information available for ongoing processing. For example, when navigating through traffic, it is important to remember surrounding objects (e.g., overtaking cars) for a few seconds even when we are directing our gaze and attention elsewhere. These VWM representations should include information on various features of these objects (e.g., their shape, color, location, direction of movement, etc.). This is a nontrivial task as these different feature dimensions are processed by various feature-specific modules (Corbetta & Miezin, 1990; Goodale & Humphrey, 1998; Livingstone & Hubel, 1988; Mecklinger & Pfeifer, 1996; Ungerleider & Haxby, 1994). Objects are hence represented as distributed entities, and cohesive memory representations rely on feature *binding*. Feature binding serves to integrate various stimulus features and enables us to remember bound objects, for example, that we need to let a big white off-road vehicle overtake on the left (rather than a small red convertible car on the right) before we change lanes (cf. Chalfonte & Johnson, 1996; Norman & O'Reilly, 2003; Oberauer, 2005; Wheeler & Treisman, 2002).¹

The binding mechanisms in VWM are not yet fully understood. One of the most debated questions is whether feature binding is an automatic process that requires little or no cognitive resources, or whether it is an active, resource-demanding process. Some feature memory studies using change-detection tasks have argued that VWM can hold about three to four items irrespective of the constituent number of features. For example, when presented with four stimuli consisting of eight features (either four colored line bars of different orientations or four bi-colored squares), memorizing the eight features in total has been found to be as accurate as memorizing only four colors or orientations—which suggests VWM binding is automatic (Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001; see also Lee & Chun, 2001). However, others have not been able to replicate Luck and Vogel's (1997)

finding when using bi-colored objects (Delvenne & Bruyer, 2004; Olson & Jiang, 2002; Parra, Abrahams, Logie, & Della Sala, 2009; Wheeler & Treisman, 2002; Xu, 2002a), and the evidence from replications using dual-feature objects (e.g., color and orientation, or color and location) has been mixed, with some studies supporting Luck and Vogel's findings (e.g., Olson & Jiang, 2002; see also Xu, 2002a) but not others (Wheeler & Treisman, 2002; Xu, 2002b).

Also, the Luck and Vogel studies (Luck & Vogel, 1997; Vogel et al., 2001) have been criticized for not involving a stringent test of binding: To-be-rejected lures in their memory tests contained novel (i.e., unstudied) feature values and could hence be rejected based on memory for the features alone (e.g., after studying a display with a red square and a blue triangle, the test display could include a to-be-rejected *yellow* square or blue *circle*). To address this limitation, researchers have introduced a variant of the change-detection paradigm, which we will refer to as the “conjunction-detection” paradigm. This paradigm directly tests memory for feature conjunctions in that it requires differentiation of identical repetitions of study stimuli from novel *recombinations* of features that were all present in the study display (e.g., detecting a red triangle as a new object when a red square and a blue triangle had been studied). Studies using this paradigm have typically found memory for conjunctions to be poorer than memory for the individual features (Johns & Mewhort, 2002; Parra et al., 2009; Stefurak & Boynton, 1986; Treisman, Sykes, & Gelade, 1977). This suggests that binding does come at a cognitive cost.

Other studies have employed cognitive load—giving participants a concurrent secondary task in addition to the memory task—to investigate the automaticity of binding. Some of these studies have found that imposing a cognitive load does not affect binding, such that conjunction memory is no more affected by a secondary task than feature memory, again suggesting automatic feature binding (R. Allen, Baddeley, & Hitch, 2006). Other studies,

however, reported that binding is specifically impaired by a secondary task that competes for processing demands—which suggests that binding is a resource-demanding process (Elsley & Parmentier, 2009; Postma & De Haan, 1996).

One factor that has long been known to have an impact on binding processes but has received relatively little attention in the debate is unitization (cf. Asch, Ceraso, & Heimer, 1960; Ceraso, 1985, 1990; Garner, 1974; Wilton, 1989). It has been proposed that binding mechanisms differ depending on whether the to-be-bound information *intrinsically* belongs to a perceptual unit (typically referred to as an ‘object’) or whether binding involves *extrinsic*, more contextual information—a distinction that has been influential in theories of perception (e.g., G. Humphreys, 1998). Interestingly, the above-mentioned memory studies investigating effects of cognitive load have looked at *extrinsic* object-location bindings (Elsley & Parmentier, 2009; Postma & De Haan, 1996) versus *intrinsic* shape-color bindings (R. Allen et al., 2006), and found that load had an effect only in the former case (but see L. Brown & Brockmole, 2010). Troyer and Craik (2000) reported findings consistent with this. They defined an intrinsic object feature as “*an incidental aspect of the stimulus itself, such as color, font, or voice of presentation. Extrinsic context is not part of the stimulus itself, but presumably part of the overall encoded event*” (p. 161). They reported effects of cognitive load only on extrinsic bindings of words to temporal positions, not on intrinsic word-color bindings.² These cognitive load studies suggest that it may only be extrinsic binding, integrating objects with contextual aspects of stimulus processing, that is resource-demanding. However, the situation remains inconclusive as other studies have failed to find specific effects of cognitive load manipulations on extrinsic (cross-modal or object-location) binding (R. Allen, Hitch, & Baddeley, 2009; Cowan, Naveh-Benjamin, Kilb, & Saults, 2006).

A number of studies have recently aimed to contrast intrinsic and extrinsic binding in VWM directly. Xu (2002a, 2002b, 2006) has suggested that encoding of feature conjunctions

into VWM is worse when the features belong to different objects than when they are from the same object (and in fact best when they are from the same object *part*). This is taken as evidence that memory encoding, and in particular feature binding during encoding into VWM, is object-based. In other words, intrinsic binding seems to be easier than extrinsic binding.

Delvenne and Bruyer (2004) looked at the binding of abstract shapes and textures, whereby texture was either an intrinsic feature of the shapes, or presented extrinsically in the background of the shapes. Their participants' task was to discriminate between identical study-test repetitions and shape-texture recombinations. When texture was intrinsic, performance was as accurate as in a control condition where only memory for the individual features was tested. If texture was extrinsic, however, performance dropped. This pattern of results suggests that extrinsic binding is less automatic and reliable, and/or results in a less stable representation, than intrinsic binding. However, the difference between intrinsic and extrinsic binding mainly arose when study displays contained four (as opposed to two) items, in which case performance in the extrinsic binding conditions was at chance level; hence it is unclear if the distinct binding effects arose from differences in maintenance or retrieval processes, or simply from a failure to encode the extrinsic shape-texture association in the first place.

Finally, Karlsen, R. Allen, Baddeley, and Hitch (2010) recently contrasted intrinsic and extrinsic shape-color binding. They used nameable shapes and colors (in the extrinsic case color was presented as a disjunct color square), and their participants had to distinguish identical study-test repetitions from recombinations. They found that performance was superior with intrinsic stimuli. However, their test probes were always intrinsic and thus they were always perceptually incongruent with the extrinsic study item(s), which may have contributed to this result. They also found that intrinsic and extrinsic binding were equally affected by cognitive load. This could be taken to imply that neither type of binding is

resource-demanding, but the authors deemed this implausible, and suggested instead that binding may be automatic in the intrinsic case and “strategic but relatively cost-free” in the extrinsic case.

In sum, the literature suggests that intrinsic binding may be more efficient and/or more automatic than extrinsic binding, but there is much inconsistency (for an extensive review from a neuroscience point of view, see Zimmer, 2008), and there are several complicating factors. We discuss three of these: Firstly, some of the previous studies confounded the intrinsic-extrinsic factor with feature dimension, for example comparing color as an intrinsic feature with location as an extrinsic feature, hence allowing no strong conclusions to be made.

Secondly, some of the previous studies used easily nameable features, such as digits, geometric shapes and focal colors. While this may be appropriate in long-term recognition experiments with dozens of items, explicit naming in working memory is likely to blur any differences between intrinsic and extrinsic binding (cf. Walker & Cuthbert, 1998).

To the best of our knowledge, the Delvenne and Bruyer (2004) study is the only study that avoided both these pitfalls.³ Yet, they investigated intrinsic versus extrinsic binding via a conjunction-detection task which yielded chance-level performance in their extrinsic condition, hence precluding strong inferences as to whether the differential intrinsic versus extrinsic binding effects were based on maintenance and retrieval processes, or a failure to encode the extrinsic association.

Thirdly, the use of the conjunction-detection paradigm used in virtually all of the above-mentioned binding studies carries an additional disadvantage, even though the task requires differentiating between identical repetitions and feature recombinations (so a correct decision must rely on memory for the conjunction): By design, traditional conjunction-detection tasks using two features cannot be used to investigate obligatory binding. This is because both features are by definition task-relevant (some of these studies also include

conditions where only one feature is monitored, but then the other, task-irrelevant feature is never manipulated). Therefore, conjunction-detection tasks can demonstrate that feature conjunctions are best encoded when both features are from the same object (Delvenne & Bruyer, 2004; Karlsen et al., 2010; Xu, 2002a, 2002b, 2006), but they cannot determine whether binding is truly automatic and obligatory, or whether only task-relevant features are obligatorily bound. This applies to both initial binding at the encoding stage, and the reintegration at the retrieval stage.⁴

Given this backdrop, the present paper aims to (1) confirm that differences between intrinsic and extrinsic binding exist in VWM, (2) establish whether these differences can be framed in terms of obligatory binding, and (3) determine how these differences may be governed by both encoding and retrieval processes. It adopts a methodology different from that used in the research reported above, and one which has been successfully used in working memory binding studies previously (e.g., Maybery et al., 2009), namely an *irrelevant congruence* paradigm. This paradigm requires participants to ignore one of the feature dimensions and assesses their performance in making recognition judgments regarding the other feature dimension. A study-test manipulation of the ignored (i.e., irrelevant) feature is then implemented. If study-test congruence of the irrelevant feature affects performance in the judgment of the relevant dimension—that is, if an irrelevant study-test change leads to a drop in accuracy or an increase in RT—these effects are then taken to demonstrate binding. The crucial comparison in this method is hence the comparison between an identical-repetition condition, in which the test probe is identical to a study stimulus (i.e., the conjunction of feature values is unchanged from study to test), and a recombination condition, in which both feature values of the test probe are ‘old’ but drawn from different study stimuli (i.e., presented in an unstudied recombination).

For example, after studying a red square and a blue triangle, a participant could be presented with a test stimulus and asked whether they had studied that particular shape, independent of its color (i.e., make an old/new shape judgment). If the test probe is a square, the correct answer would be ‘old’, irrespective of the color of the test square. However, the accuracy or RT difference between a red test square (i.e., an identical repetition) and a blue test square (i.e., a recombination) would demonstrate the existence and use of a bound representation of the study shape (square) and the study color (red).

In our opinion, this paradigm is particularly well suited for the investigation of feature binding for the following three reasons: (1) As mentioned above, it allows for the investigation of obligatory binding, that is, binding independent of task-relevance. The paradigm allows a variation of instructions such that one of the features can be made task-irrelevant (either at the time of retrieval or at both encoding and retrieval), while still allowing the assessment of effects of its study-test congruence. (2) Both relevant classes of items (identical repetitions and recombinations) consist only of studied features (unlike some variants of the change-detection paradigm; cf. Luck & Vogel, 1997). (3) Both relevant classes of items call for the same response (unlike the standard change-detection paradigm). The only difference between the two relevant classes hence lies in a task-irrelevant dimension, and varying levels of integration of this task-irrelevant feature dimension is the only factor that could lead to performance differences between the two conditions. In other words, our paradigm substantially reduces the likelihood that the two relevant conditions rely on qualitatively different mechanisms, as has been argued for ‘same’ and ‘different’ response categories in the traditional conjunction-detection paradigm (e.g., see Cowan et al., 2006; Pashler, 1988).

Our previous work in long-term object recognition memory has successfully used this irrelevant congruence paradigm (Ecker, Groh-Bordin & Zimmer, 2004; Ecker, Zimmer &

Groh-Bordin, 2007a, 2007b; Ecker, Zimmer, Groh-Bordin & Mecklinger, 2007c; Groh-Bordin, Zimmer & Ecker, 2006; Zimmer & Ecker, 2010; see also Clark & Gronlund, 1996; Meiser & Sattler, 2007; Nicholson & Humphrey, 2003; Srinivas & Verfaellie, 2000). This research has indicated that any information that is intrinsic to an object is bound more tightly than extrinsic information. This means that at retrieval, intrinsic feature information becomes available quickly, and automatically influences object recognition even when the feature is irrelevant for the object recognition task. In contrast, the reintegration of extrinsic contextual information is slower and more controlled and hence does not influence object recognition when the extrinsic information is irrelevant, even though it is clearly accessible when participants are prompted to retrieve it. That is, subjects can accurately retrieve both intrinsic and extrinsic features if directly asked to do so; however, a task-irrelevant study-test mismatch only slows recognition if the feature is intrinsic (see in particular Ecker et al., 2007a). Based on this evidence, we have proposed that different levels of long-term memory representations exist that do or do not contain extrinsic information (Ecker et al., 2007a; Zimmer & Ecker, 2010).

A further aim of the present study was thus to test if these differential binding effects established in long-term recognition are time-scale invariant (cf. Brown, Neath, & Chater, 2007) and would hence translate to short-term working memory.

The Present Study

This study directly tested the assumption that distinctive mechanisms are involved in intrinsic and extrinsic VWM binding. We hypothesized that the binding of intrinsic object information should be easier, faster, and more automatic than the integration of object features with extrinsic information.

We present a series of experiments that tested this idea. Following precedent in long-term memory (Ecker et al., 2007b), we used the same features—color and shape—in both

intrinsic and extrinsic conditions. In all experiments, participants studied small sets of abstract 3D-shapes that were either intrinsically colored or presented on an extrinsic colored background (see Figure 1). As discussed by Delvenne and Bruyer (2004), we made sure that the extrinsic feature was not disjunct from the shape but spatially proximal, in order to minimize the difference in spatial layout—and hence the required distribution of spatial attention—between intrinsic and extrinsic conditions. Xu (2006) discussed that connectedness and proximity are the two most important aspects in determining whether a stimulus is represented as a coherent representation in VWM. We strived to make intrinsic and extrinsic stimuli as similar as possible on these dimensions to allow for a more conservative test of our intrinsic/extrinsic factor.

At test, participants made old/new recognition judgments regarding the shape and/or the color of a single test item. We chose to use a single test-item (rather than present the entire modified study array again at test) following suggestions by Wheeler and Treisman (2002) that a complex test display may destabilize the fragile bindings due to the ongoing binding requirements.

The single test item belonged to one of three test conditions: It was either an identical repetition of one of the study items (*same* condition), a novel recombination of a studied shape and a studied color (*recombined* condition), or a *new* item, with a novel shape or color not featured in the study display (cf. Figure 1). We assessed binding effects as RT or accuracy differences between the *same* and *recombined* conditions. Our main focus was on RT measures because if an incongruent (but irrelevant) feature hampers an ‘old’ decision, that does not necessarily mean it will cause rejection of the item. It is more likely it will only slow down its acceptance. (We also assessed differences in accuracy, which sometimes do and sometimes do not occur in this paradigm, most likely due to speed-accuracy trade-off.)

Experiment 1

In Experiment 1, participants were instructed to encode both shape and color dimensions while the conjunction of shape and color was task-irrelevant. As discussed earlier, this means we did not directly test memory for the conjunction of features, but tested either shape or color to assess effects of manipulations of the irrelevant dimension. Other studies using a similar task (e.g., Treisman & Zhang, 2006) reported that feature memory was impaired when task-irrelevant conjunctions were changed from study to test, suggesting obligatory binding. We hypothesized, however, that such effects would only occur with intrinsic but not extrinsic stimuli. That is, we expected a facilitative effect of keeping the combination of features intact from study to test (i.e., better performance, in particular lower RTs, in *same vs. recombined* conditions), indicative of obligatory binding of those features, for intrinsic stimuli only. We use the term ‘obligatory’ here to indicate that a feature is integrated despite its objective task irrelevance.

Method

Participants. Twenty-four undergraduate psychology students from the University of Western Australia participated in this experiment (8 males, 16 females, mean age 20.7 years, age range 17-32 years).

Apparatus. The experiment was controlled by Revolution software (RunRev Ltd., Edinburgh). Participants were tested individually in sound-attenuated booths, and stimuli were presented on a 17-in. thin-film transistor monitor.

Stimuli. We generated a set of eight abstract “Attneave” shapes with between six and eight angles (Figure 1; cf. Attneave & Arnoult, 1956; Collin & McMullen, 2002). Some spatial depth was added to the shapes to make them appear three-dimensional. There were intrinsic and extrinsic versions of each shape. In the intrinsic versions, the surface of the shapes was colored in one of eight colors, and they were presented on a square, light-gray

background. In the extrinsic condition, the shapes were colored in light-gray, but the background was colored in one of the eight colors. Stimuli were designed such that the Attneave shape covered approximately 50% of the square behind; hence the colored area was equally large in both intrinsic and extrinsic versions (see Figure 1). Colors were taken from Parra et al. (2009), who had selected eight non-focal colors that maximized discriminability while minimizing nameability. Easy verbalization of both shapes and colors would have been likely to blur any differences between intrinsic and extrinsic conditions (Walker & Cuthbert, 1998). Altogether, there were $2 \times 8 \times 8 = 128$ individual stimuli.

In the study phase of each trial, three stimuli were positioned with the aid of an invisible 3×3 grid, using a subset of the eight outer positions. Stimuli were randomly positioned but were not allowed to be arranged in a single column or row of the grid (see Figure 1). The single test probe was always presented in the central position of the grid.

Design. The experiment involved a fully crossed $2 \times 2 \times 3$ within-subjects design. The first factor was Test-Task (color / shape); on half the trials participants made their old/new decision with reference to either the color or the shape of the test probe (as indicated by an auditory cue during retention), respectively. The second factor was Stimulus-Type (extrinsic / intrinsic); half the trials used extrinsic stimuli, half used intrinsic. The third factor was Congruence (new / recombined / same). For each combination of Test-Task and Stimulus-Type, 32 trials used a novel test probe (*new* condition; correct response ‘new’). In the color task, this was a studied shape in an unstudied color (i.e., one of the eight colors in the set, but one that was not featured in that trial’s study phase; see forth column of test items in Figure 1); in the shape task, this was an unstudied shape in a studied color (see third column of test items in Figure 1). Twenty-four trials used a novel recombination of a studied shape and a studied color (*recombined* condition; correct response ‘old’; see second column of test items in Figure 1), and 24 trials used an identical repetition as the test probe (*same* condition;

correct response ‘old’; see first column of test items in Figure 1). The trial sequence was determined in a quasi-random fashion. Altogether, there were 320 study-test trials.

Procedure. Participants were instructed to memorize on each trial the three colors and the three shapes; no reference to the conjunction of features was made. However, instructions made clear that there would be recombined test probes, to prevent surprise and confusion. Participants were informed that they would receive performance feedback at the end of the session.

Each trial commenced with a centrally presented fixation cross (500 ms). Then three study items were presented simultaneously in their grid positions for 4 s. The blank-screen retention interval was 2 s. In the middle of the retention interval, an auditory cue was presented via loudspeakers, specifying the upcoming memory task. The cue was either “color” or “shape” (both cues spanned approximately 600 ms, so onset was about 700 ms into the retention interval), and participants were then to make an old/new decision with reference to either the color or the shape of the test probe, respectively. All presentation times were chosen to ensure acceptable performance levels (based on pilot testing), considering the abstract stimuli used and the need for an auditory cue during retention, while remaining clearly within the boundaries of VWM’s time frame. The cue was auditory and not visual to reduce interference. The maximum response time was set at 2 s; the test probe disappeared after this 2 s interval or on a key press. The ‘Z’ and ‘/’ keys of a standard English keyboard, labeled “NEW” and “OLD”, were used as response keys; response-to-key mapping was counterbalanced across participants. The inter-trial interval was 1 s. There was a self-paced break after every 80 trials. Participants received performance feedback (% correct responses) at the end of the session.

Results

Descriptive statistics for accuracy and RT are given in Table 1. For the sake of conciseness, throughout the remainder of the paper we will only report follow-up analyses for those contrasts that are directly relevant to our hypotheses.

Accuracy analyses. A $2 \times 2 \times 2$ repeated measures analysis of variance (ANOVA) on hit rates, with factors Test-Task (color / shape), Stimulus-Type (extrinsic / intrinsic), and Congruence (recombined / same) only yielded a significant effect of Stimulus-Type, $F(1,23) = 22.97$, $MSE = .004$, $p < .001$, $\eta_p^2 = .50$, indicating a higher hit rate for intrinsic stimuli overall. Hence, there was no evidence for shape-color binding in performance accuracy.

Additionally, in order to assess task difficulties, we calculated *Pr* discrimination scores (hit rate – false alarm rate, Snodgrass & Corwin, 1988; see also R. Allen et al., 2006), collapsing hit rates across *same* and *recombined* stimuli. A 2×2 Test-Task (color / shape) by Stimulus-Type (extrinsic / intrinsic) ANOVA on these scores yielded a main effect of Test-Task, $F(1,23) = 13.71$, $MSE = .018$, $p = .001$, $\eta_p^2 = .37$, and a main effect of Stimulus-Type, $F(1,23) = 13.01$, $MSE = .005$, $p = .002$, $\eta_p^2 = .36$, as well as a marginally significant interaction, $F(1,23) = 3.51$, $MSE = .004$, $p = .07$, $\eta_p^2 = .13$. This means that the color task was easier than the shape task (an effect relying exclusively on an increased false alarm rate in the shape task; see Table 1, cf. R. Allen et al., 2006, for a similar effect), and that only the shape task was affected by Stimulus-Type, such that shape judgments were easier with intrinsic stimuli (the advantage of intrinsic stimuli in the shape task rested mainly on an increased hit rate; cf. Table 1).

RT analyses. Reaction time analysis was based on mean RTs for correct responses, with outliers (± 3 SDs from individual mean) and RTs below 200 ms removed (for some individuals, the 3SD criterion did not eliminate some unduly short RTs). Response times were

lower and more uniform in the color task; correct rejections of *new* items were delayed relative to hits for *same* and *recombined* probes only in the shape task (see Table 1). This was confirmed by a $2 \times 2 \times 2$ Test-Task (color / shape) by Stimulus-Type (extrinsic / intrinsic) by Congruence (new / recombined / same) ANOVA returning a significant interaction between Test-Task and Congruence, $F(2,46) = 64.89$, $MSE = 3438$, $p < .001$, $\eta_p^2 = .74$. This pattern is in line with the accuracy analysis, which found the color task to be easier. It suggests that participants were able to do the color task without actually focusing on the shape aspect of the test stimulus, presumably relying on the high salience of color.

To assess binding effects, a $2 \times 2 \times 2$ Test-Task (color / shape) by Stimulus-Type (extrinsic / intrinsic) by Congruence (recombined / same) ANOVA on hit RTs was conducted. This analysis yielded a three-way interaction, $F(1,23) = 6.11$, $MSE = 1421$, $p = .02$, $\eta_p^2 = .21$, which was due to the abovementioned uniformity of RTs in the color task on the one hand, and a distinct pattern of RTs in the shape task on the other (see Table 1). Mean RTs across conditions in the color task were within 14 ms of each other, and hence a separate Stimulus-Type by Congruence ANOVA yielded no significant effects (all F s < 1).

By contrast, the analogous analysis in the shape task yielded the expected interaction between Stimulus-Type and Congruence, $F(1,23) = 7.06$, $MSE = 1533$, $p = .01$, $\eta_p^2 = .23$. Planned contrasts confirmed that this interaction was due to the fact that the difference between *same* and *recombined* conditions was significant with intrinsic stimuli, $F(1,23) = 39.58$, $p < .001$, $\eta_p^2 = .63$, but not extrinsic stimuli, $F(1,23) = 1.28$, $p = .27$, $\eta_p^2 = .05$ (see Figure 2).

Discussion

Experiment 1 yielded two clear findings. First, color recognition was not affected by the manipulation of shape features from study to test, irrespective of intrinsicity. The uniformity and speed of responses across conditions in this task suggests that people were able to make

color judgments without fully processing the shapes, perhaps based on the high salience of color. De Jonghe (2008) reported a similar effect, with a color task unaffected by shape manipulations. Logie et al. (2011) likewise found that irrelevant shape manipulations did not affect short-term memory accuracy for color-location conjunctions, while manipulations of irrelevant color tended to affect memory for shape-location conjunctions. In the following, we will therefore focus on the shape task.

In the shape task, there was response facilitation when the test stimulus matched a specific study item in both shape and (task-irrelevant) color, but only when color was an intrinsic feature of the object. This allows three conclusions: (a) Shape and intrinsic color were bound at encoding, even though participants were not explicitly instructed to encode the conjunction; the representation used to make a shape judgment hence contained color information when color was an intrinsic feature of the object. (b) Intrinsic color information was involuntarily activated at retrieval, affecting shape recognition performance despite being irrelevant. (c) Extrinsic color information was either not obligatorily bound to the shape at encoding, or, if it was bound, extrinsic color information was not automatically activated at retrieval.

Experiment 1 confirmed our hypotheses and established that shape recognition was involuntarily affected by intrinsic but not extrinsic shape-color binding when both features were encoded intentionally (although not the conjunction). Two subsequent experiments were designed to explore binding effects after completely incidental study of color (Experiment 2), and after intentional encoding of the shape-color conjunction (Experiment 3).

Experiment 2

Experiment 2 was designed to test whether there would be obligatory intrinsic binding, and binding-based facilitation of shape recognition, if color was not only irrelevant for the test task, but also only incidentally encoded. That is, in Experiment 2, color was completely

irrelevant—it was incidentally encoded and never tested. We used only the shape task from Experiment 1, and only the intrinsic stimulus type, as Experiment 1 had clearly found no binding effect for extrinsically colored stimuli even if color was intentionally encoded.

Method

Participants. Twenty-four undergraduate psychology students from the University of Western Australia participated in this experiment (7 males, 17 females, mean age 20.3 years, age range 17-25 years). None of these had participated in Experiment 1.

Apparatus, Stimuli, Design, and Procedure. Experiment 2 was identical to Experiment 1, with the following exceptions: (a) Experiment 2 employed only the shape task of Experiment 1, and there was hence no auditory cue in the retention interval. (b) Only intrinsically colored stimuli were used. (c) Participants were instructed to ignore color completely. (d) There were only 80 study-test trials (32 *new*, 24 *recombined*, 24 *same*) in a single-factor within-subjects design.

Results

Descriptive statistics for accuracy and RT are given in Table 2.

Accuracy analyses. A one-way repeated measures ANOVA on shape task hit rates, with the single factor of color Congruence (*recombined* / *same*), showed that identical repetition facilitated shape recognition, $F(1,23) = 4.99$, $MSE = .003$, $p = .04$, $\eta_p^2 = .18$.

RT analyses. The analogue analysis on hit response times showed that identical repetitions also yielded faster reactions than recombined repetitions, $F(1,23) = 6.07$, $MSE = 5241$, $p = .02$, $\eta_p^2 = .21$.

Discussion

Experiment 1 suggested that intrinsic color may be obligatorily bound to shape at study, but it did not provide compelling evidence. This is because it would have been a reasonable strategy to encode three bound objects rather than six individual feature values,

when both feature dimensions were potentially relevant at test. Experiment 2, however, provides clear evidence for obligatory intrinsic color-shape binding by demonstrating that identical (color-congruent) repetition leads to quicker responses and higher accuracy, even when the intrinsic feature is completely irrelevant to the shape recognition task. It follows that intrinsic color is not only involuntarily retrieved during a shape recognition test when instructions make sure that it is encoded (as in Experiment 1), but that intrinsic color is encoded into VWM and bound to shape obligatorily even when it is completely irrelevant. Together, Experiments 1 and 2 suggest that intrinsic but not extrinsic object features are encoded and retrieved obligatorily, which supports the view that there are distinct intrinsic and extrinsic binding mechanisms in VWM.

Experiment 3

We did not find evidence for extrinsic color binding in Experiment 1. As participants in Experiment 1 were not instructed to memorize the shape-color conjunctions, and as tasks could be performed without relying on the conjunctions, it was unclear whether the lack of extrinsic binding effects was due to the fact that extrinsic color was not bound to shape at encoding, or whether bound extrinsic color was not automatically reactivated at retrieval. Experiment 3 was designed to test whether shape-color binding effects for extrinsic stimuli would occur in a shape task if subjects were encouraged to encode the conjunction of features.

Method

Participants. Twenty-eight undergraduate psychology students from the University of Western Australia participated in this experiment (7 males, 21 females, mean age 19.8 years, age range 17-24), having not participated in Experiment 1 or 2.

Apparatus, Stimuli, Design, and Procedure. Experiment 3 was identical to Experiment 1, with the following exceptions: (a) Experiment 3 employed a two-stage task (cf. Ecker et al., 2007a, for a precedent). On each trial there was an initial speeded shape task, with a

maximum response time of 1400 ms (roughly corresponding to the mean correct rejection RT + 2 SDs in the shape task of Experiment 1). This was done to ensure participants focused on the shape task without voluntarily attempting to incorporate color information into their decision, while not, however, putting them under undue time pressure. On-screen feedback (“Too slow!”) appeared for 1 s if no response was made in time, and the experiment continued with the next trial. In case of an ‘old’ response, the shape task was followed by a color task, in which participants were asked to decide whether the color of the item (i.e., the shape identified as old) had or had not changed from study to test. The test probe remained on the screen after the shape task response and an auditory cue (“Same color?”) signaled the onset of the second task. There was no time limit for the color task; the test probe disappeared when a color task response was made. Response keys were counterbalanced across subjects but the same key was always used for ‘old’ responses in both tasks. (b) Participants were instructed to encode the conjunction of color and shape for each item. (c) There were 160 study-test trials in a 2 (Stimulus-Type: extrinsic / intrinsic) \times 3 (Congruence: new / recombined / same) within-subjects design.

We hypothesized that intrinsic color congruence would affect shape recognition but that extrinsic color congruence would not. In the color task, however, we expected that participants would be equally able to retrieve the shape-color conjunction in both intrinsic and extrinsic conditions (replicating the long-term recognition findings of Ecker et al., 2007a).

Results

Limiting the analyses to responses below the 1400 ms cut-off resulted in the exclusion of 9% of all trials (8% of all correct responses)⁵. Descriptive statistics for accuracy and RT are given in Table 3.

Accuracy analyses. A repeated measures ANOVA on shape task hit rates, with the factors Stimulus-Type (extrinsic / intrinsic) and Congruence (recombined / same), yielded a

main effect of Congruence, $F(1,27) = 20.59$, $MSE = .007$, $p < .001$, $\eta_p^2 = .43$, which was qualified by a marginally significant interaction, $F(1,27) = 3.33$, $MSE = .009$, $p = .08$, $\eta_p^2 = .11$. This suggested a stronger binding effect for intrinsic as opposed to extrinsic stimuli (see Figure 3). Follow-up contrasts confirmed this: The *same – recombined* binding effect was significant for intrinsic stimuli, $F(1,27) = 21.97$, $MSE = .007$, $p < .001$, $\eta_p^2 = .45$, but not extrinsic stimuli, $F(1,27) = 2.42$, $MSE = .009$, $p = .13$, $\eta_p^2 = .08$.

However, analysis of the color task indicated a significant difference in explicit color memory between extrinsic and intrinsic conditions. A one-way ANOVA on color discrimination scores (*Pr* scores, considering ‘same color’ responses to *same* items hits and ‘same color’ responses to *recombined* items false alarms) showed that color recognition was better for intrinsic ($Mean = .47$, $SE = .04$) than extrinsic stimuli ($Mean = .38$, $SE = .04$), $F(1,27) = 4.60$, $MSE = .016$, $p = .04$, $\eta_p^2 = .15$. Even though direct color recognition was well above chance even for extrinsic stimuli, $t(23) = 8.39$, $p < .001$, the pattern of binding for accuracy (reported in the preceding paragraph) could result at least partially from superior color memory in the intrinsic condition—in other words, if the shape-color association is not as well represented in memory for extrinsic stimuli, it would not be surprising that shape recognition is less affected by a color match or mismatch.

We therefore repeated the shape task accuracy analysis, with the difference in extrinsic versus intrinsic color recognition performance as a covariate. This rendered the Stimulus-Type by Congruence interaction nonsignificant, $F(1,26) = 1.27$, $MSE = .008$, $p = .27$, $\eta_p^2 = .05$.

RT analyses. Analyses of shape task hit reaction times were carried out after outliers more than 3 SDs from the mean or below 200 ms were removed on an individual subject basis. A repeated measures ANOVA with the factors Stimulus-Type (extrinsic / intrinsic) and Congruence (recombined / same) yielded a main effect of Congruence, $F(1,27) = 17.45$,

$MSE = 2520, p < .001, \eta_p^2 = .39$, which was qualified by a significant interaction, $F(1,27) = 8.81, MSE = 2776, p < .01, \eta_p^2 = .25$ (see Figure 4). Follow-up contrasts confirmed a significant *same – recombined* binding effect for intrinsic stimuli, $F(1,27) = 18.48, MSE = 3627, p < .001, \eta_p^2 = .41$, but not for extrinsic stimuli, $F < 1$.

To test whether this effect pattern was influenced by differences in color recognition, we repeated the analysis with the difference in intrinsic vs. extrinsic color recognition performance as a covariate. This had no impact on the Stimulus-Type by Congruence interaction, which remained significant, $F(1,26) = 8.09, MSE = 2867, p < .01, \eta_p^2 = .24$.

Discussion

In Experiment 3 we again found clear evidence for shape-color binding in RT when color was an intrinsic object feature. In contrast, we again found no evidence for an obligatory influence of extrinsic color-shape binding on shape recognition, even when people intentionally encoded the conjunction of shape and color, and could demonstrably retrieve the shape-color association if directly prompted to do so.

There are two interpretations of this result pattern, which differ only marginally. One possibility is that extrinsic color information forms part of the memory representation used in the shape task, but that the part of the representation that holds extrinsic information is not activated at retrieval. The alternative interpretation is that the representation used in the shape task does not include extrinsic color information while the representation used in the subsequent color task does. This would then imply that there are either two distinct types of representation—one that includes only item information, and a higher-level representation incorporating contextual information (cf. Ecker et al., 2007a; Zimmer & Ecker, 2010)—, or that contextual information takes more time to be re-integrated at retrieval (cf. Brockdorff & Lamberts, 2000; Kent & Lamberts, 2006). Given that recollection of contextual detail is usually assumed to take place within about 600 to 800 ms (cf. Gronlund & Ratcliff, 1989;

McElree, Dolan, & Jacoby, 1999; Düzel, Yonelinas, Mangun, Heinze, & Tulving, 1997), we argue that the former alternative is more likely.

Our interpretation also implies that binding at encoding and reintegration at retrieval are separate processes. An integration of features at encoding makes the conjunction *potentially* retrievable, but binding at encoding does not guarantee reintegration at retrieval. In Experiment 3, shape and extrinsic color are clearly bound at encoding, but reintegration (or in other words, access to an integrated representation) only took place “on demand”, that is, when the task involved a judgment of the conjunction, not when it involved only an assessment of shape.

In sum, the results of Experiment 3 suggest that intrinsic but not extrinsic feature information is obligatorily activated during object recognition. This speaks for the existence of distinct memory representations in VWM supporting item and item-plus-context recognition, respectively.

The final experiment investigated the question of whether we could find binding effects with our extrinsic stimuli if we instructed participants to treat them *as if* they were intrinsically colored.

Experiment 4

Arguably, our intrinsic versus extrinsic distinction is somewhat arbitrary despite the fact that it is grounded in theories of perception (e.g., G. Humphreys, 1998). Ideally, one would like an independent criterion to determine if a given feature should be considered an intrinsic or extrinsic feature. The current literature lacks such a criterion, and research can only rely on the assertion that whatever is perceived as part of the stimulus should be called intrinsic, and everything else extrinsic. To test the validity of this assumption, we sought to manipulate the way the stimulus feature color was perceived. To this end, Experiment 4 used only stimuli in which the color was presented in the square surrounding the abstract polygon

shape, but in two different conditions. One condition mimicked the extrinsic condition of earlier experiments in that the colored squares were presented on a white screen, and participants were instructed to encode the gray foreground polygon shapes and the colors of the background squares (the *separable* condition). The other condition (the *unitized* condition) used the exact same stimuli, but these were presented on a gray screen, which matched the color of the gray foreground shapes (see Figure 5). Participants were instructed to encode the shape and color of the resulting frame-like stimuli (i.e., intrinsically colored square shapes with polygon holes). Therefore, both the presentation format (in a bottom-up sense) and the encoding instructions (in a top-down sense) were manipulated in order to jointly create the perception of intrinsic versus extrinsic color.

We hypothesized that the intrinsicity of a feature is determined by the perception of the feature as belonging to an object. It follows that a color manipulation in the separable condition—where color should be perceived as belonging to the background of the to-be-remembered shape—should replicate the findings of the extrinsic condition from the previous experiments. That is, we expected no effect of color congruence on shape recognition in the separable condition. In contrast, color should be perceived as an intrinsic feature of the frame-like stimuli in the unitized condition. In this case we hence expected a replication of the findings of the intrinsic condition from the previous experiments. That is, we expected an effect of color congruence on shape recognition in the unitized condition.

For the color task, we again expected that participants could retrieve the color-shape conjunctions when prompted to do so in both separable and unitized conditions.

Method

Participants. Sixty undergraduate psychology students from the University of Western Australia participated in this experiment (19 males, 41 females, mean age 21.1 years, age range 17-34 years). None of these had participated in earlier experiments.

Apparatus, Stimuli, Design, and Procedure. Experiment 4 was similar to Experiment 3, with the following exceptions: (a) Experiment 4 used only stimuli in which the color was contained in the (background) squares. (b) The 3D-effect of the gray polygon shapes was reduced, and an equivalent, small 3D-effect was added to the colored square backgrounds. In previous experiments, the 3D-effect was added to the gray foreground shapes to allow a clear figure-ground separation; that is, to ensure the gray shape was perceived in front of the square background. A reduced 3D-effect applied equally to both the polygon shape and the colored square were necessary to make the entire stimulus ambivalent in terms of figure-ground separation, allowing participants to perceive the object either as a gray, polygon shape in front of a colored, square background, or a colored, square, frame-like shape with a polygon hole (see Figure 5). (c) Rather than a Stimulus-Type factor, there was a between-subjects factor of Presentation/Instruction (separable / unitized). (d) There was a single within-subjects factor of color Congruence, and there were 80 study-test trials (32 *new*, 24 *recombined*, 24 *same*).

Results

Limiting the analyses to responses below the 1400 ms cut-off resulted in the exclusion of 12% of all trials (11% of all correct responses)⁵. Descriptive statistics are given in Table 4.

Accuracy analyses. A mixed-design ANOVA on shape-task hit rates, with factors Presentation/Instruction (separable / unitized) and Congruence (recombined / same) yielded a main effect of Congruence, $F(1,58) = 9.71$, $MSE = .008$, $p < .01$, $\eta_p^2 = .14$. Although the apparent interaction was not statistically reliable, $F(1,58) = 2.16$, $MSE = .008$, $p = .15$, $\eta_p^2 = .04$, planned contrasts showed a significant *same – recombined* binding effect in the unitized condition, $F(1,29) = 13.62$, $MSE = .006$, $p < .001$, $\eta_p^2 = .32$, but not in the separable condition, $F(1,29) = 1.10$, $MSE = .009$, $p = .30$, $\eta_p^2 = .04$ (see Figure 6).

RT analyses. The analogue analysis on shape task hit response times yielded a main effect of Congruence, $F(1,58) = 12.83$, $MSE = 2720$, $p = .001$, $\eta_p^2 = .18$, which was qualified

by a significant Presentation/Instruction by Congruence interaction, $F(1,58) = 4.55$, $MSE = 2720$, $p = .04$, $\eta_p^2 = .07$ (cf. Figure 7). Again, planned contrasts indicated that there was a *same – recombined* binding effect in the unitized condition, $F(1,29) = 13.87$, $MSE = 3201$, $p < .001$, $\eta_p^2 = .32$, but not the separable condition, $F(1,29) = 1.28$, $MSE = 2238$, $p = .27$, $\eta_p^2 = .04$.

Presentation/Instruction conditions did not differ in direct color recognition performance in the color task (separable: $Mean = .33$, $SE = .03$; unitized: $Mean = .37$, $SE = .03$), as determined by a one-way ANOVA on discrimination scores, $F < 1$.

Discussion

Experiment 4 demonstrated that stimuli that failed to elicit shape-color binding effects in Experiments 1 and 3—consisting of a gray shape in front of a colored background—did give rise to such shape-color binding effects when participants were led to process the features as parts of a unified stimulus—a colored, frame-like object in front of a uniform gray background. This is additional evidence that features produce binding effects if they are processed as intrinsic features of an object (cf. Delvenne & Bruyer, 2004; Xu, 2002a, 2002b, 2006). This result underscores the assumption that ‘intrinsicity’ is not a rigidly assessable dimension of features, but is determined by perception, which in turn depends on visual grouping and Gestalt principles (Wertheimer, 1923/1958) as well as strategies and expectations (cf. Bar, 2004).

General Discussion

We presented a series of experiments demonstrating that (a) intrinsic color is obligatorily encoded into VWM together with the shape of an object, (b) intrinsic color is involuntarily retrieved alongside shape information, affecting performance in short-term shape recognition, (c) extrinsic color does not affect short-term shape recognition even when its association to shape is encoded and retrievable on demand. Finally, we also reported the

first demonstration that (d) perception indeed determines to a certain degree if a feature is processed as an intrinsic or extrinsic object feature. Before we discuss the theoretical implications of these findings, we will discuss an aspect of our results that could be seen to be at odds with our interpretation of obligatory intrinsic binding. This aspect pertains to the symmetry of binding effects.

Asymmetric Binding—Feature Dominance or Relative Discriminability?

If binding of intrinsic features is obligatory, why did we not find evidence for binding in the color task used in Experiment 1? In other words, if shape and color were bound even when their conjunction was task-irrelevant—as demonstrated by the results of the shape task, where a change in irrelevant color affected shape recognition—then why did a change in irrelevant shape not have an impact on the recognition of color? We mentioned before that this pattern may have occurred because the high-salience characteristics of color obviated the need for full-fledged processing of shape during recognition; that is, color judgments may have been possible without fully processing the associated probe shape. Mean reaction times uniformly under 800 ms in the color task lend some support to this assertion. Indeed, there is some evidence that color per se may be more salient than other features both in infants (e.g., Kaldy, Blaser, & Leslie, 2006) and adults (Hannus, van den Berg, Bekkering, Roerdink, & Cornelissen, 2006; see also Olds, Graham, & Jones, 2009). Hence, to the degree that color is a dominant feature, color judgments may be relatively uninfluenced by other features.

An alternative viewpoint, however, is that there is no fixed salience hierarchy such that some features (and/or changes to these features) are more salient than others—instead, salience may depend on relative feature contrast or discriminability (Maybery, Leung, Tearne, van Valkenburg, & Parmentier, 2012; Melara & Mounts, 1993; Sobel & Cave, 2002; Theeuwes, 1994; van den Berg, Cornelissen, & Roerdink, 2008). This would imply that recognition decisions on the more discriminable feature dimension may require less

processing and potentially less integration across feature dimensions. In our task, the colors were clearly more discriminable than the shapes, hence this seems to be a plausible explanation for the lack of binding effects found in the color task.

Such asymmetries present a challenge for strict interpretations of object-based models of memory (e.g., Gajewski & Brockmole, 2006; Vogel et al., 2001) because it seems that depending on factors such as salience or discriminability, processing of an individual feature might yield enough information to trigger a recognition decision with above-threshold confidence. However, if additional information is required to reach that threshold, more holistic object representations are accessed, and during this time-consuming re-integration process, “strong” features may support “weak” features—but only if the two are bound within the object representation. Future research will need to systematically investigate the roles of salience, discriminability, and time. For now, we note that this issue does not at all qualify our main conclusion that intrinsic but not extrinsic feature manipulations impact on short-term object recognition.

A Common Principle of Cognition—Theoretical Implications

In the following, we will claim that our intrinsic/extrinsic distinction is an important dimension relevant to various areas of cognition.

The link between long-term and short-term recognition. The distinction between intrinsic and extrinsic binding has some tradition in cognitive episodic long-term memory research. Troyer and Craik (2000) reported that only long-term memory for intrinsic conjunctions was unaffected by divided attention manipulations at study and test. They argued that intrinsic binding was relatively automatic, while contextual integration required more attentional resources and intentional processing. Reder and colleagues have developed a localist network model (Diana, Reder, Arndt, & Park, 2006; Reder et al., 2000) that distinguishes two types of stimulus representations that either do or do not contain extrinsic

context information. Likewise, Zimmer and Ecker's type-token model of object long-term memory is based on the assumption that multiple types of memory representations exist that support various kinds of implicit and explicit memory functions (Ecker et al., 2004, 2007a, 2007b; Zimmer & Ecker, 2010). In particular, the model distinguishes between a representation that only contains intrinsic object information—the 'object token'—and a higher-level representation that integrates intrinsic and contextual extrinsic information—the 'episodic token'.

Zimmer and Ecker (2010) have argued, based mainly on their work using event-related potentials (ERPs; Ecker et al., 2004, 2007a, 2007b, 2007c; Ecker, Arend, Bergström, & Zimmer, 2009; Ecker & Zimmer, 2009; Groh-Bordin et al., 2006; see also Rhodes & Donaldson, 2007; Speer & Curran, 2007) that these two types of 'token' representations subserved familiarity- and recollection-based recognition, respectively. While acknowledging the achievements of single-process models of recognition (see Clark & Gronlund, 1996; Dennis & M. Humphreys, 2001; Dunn, 2004; Gillund & Shiffrin, 1984; Wixted, 2007), these studies demonstrated that only intrinsic feature manipulations automatically impacted on the presumed ERP signature of familiarity, while extrinsic feature manipulations affected only the presumed ERP signature of recollection (see Rugg & Curran, 2007, for a more general discussion of these ERP components). This maps onto the characterization of familiarity and recollection as an acontextual process and a context-integrating process, respectively (cf. Mandler, 1980; Yonelinas, 2002).

This mapping is corroborated by two related streams of fMRI work. The first stream has established that hippocampal and parahippocampal activation is associated with memory for contextual details such as source information (Cansino, Maquet, Dolan, & Rugg, 2002; Davachi, Mitchell, & Wagner, 2003), while perirhinal cortex activation is associated with

mere item memory (Davachi et al., 2003; Slotnick, Moo, Segal, & Hart, 2003; see Eichenbaum, Yonelinas, & Ranganath, 2007, for a more general review).

The second stream has more recently established that the calculation of a neural familiarity signal along the ventral visual pathway including the perirhinal cortex is sensitive to associative information if the association is a within-item association. That is, familiarity serves memory for unitized objects, and hence the calculation of item familiarity does involve binding, but only intrinsic binding (Diana, Yonelinas, & Ranganath, 2008; Staresina & Davachi, 2008, 2010).

Likewise, in the neuropsychological literature on the effects of medial temporal lobe damage on long-term episodic memory, a common distinction is made between conjunctive and relational integration, which maps onto our intrinsic/extrinsic dimension (Mayes, Montaldi, & Migo, 2007; Moses & Ryan, 2006; Ryan & Cohen, 2003). The main assumption of this theory is that the hippocampus is only necessary for bindings between items or between items and context (i.e., relational integration), while conjunctive binding of intra-item information can occur without the hippocampus (with some discussion on whether or not the hippocampus is necessary for bindings between items within a domain, e.g., two faces as opposed to a face and a name).

As Moses and Ryan (2006) discuss, the evidence for a distinction between conjunctive (intrinsic) and relational (extrinsic) binding is most compelling in the field of long-term episodic memory. The present paper argues, however, that the distinction between intrinsic and extrinsic binding is not only relevant for episodic long-term memory but is a principle that applies also to short-term working memory. Our data support the assertion that the representation used in short-term shape recognition by default includes only feature information that is intrinsic to the object, and that extrinsic information is only retrieved if necessary. This maps onto the proposed levels of representations in long-term memory

(Zimmer & Ecker, 2010), and the related ideas that an acontextual familiarity process, which binds only intrinsic information (cf. Ecker et al., 2007c), can be distinguished from a more controlled recollection process, which can integrate intra-item and contextual information, depending on task-relevance (cf. Ecker et al., 2007a; Herron & Rugg, 2003; Mayes et al., 2007).

Again, this proposal concerning short-term working memory is backed up by neuroimaging work. Piekema and colleagues have conducted a series of fMRI studies investigating intrinsic and extrinsic binding correlates in short-term recognition. In line with accounts claiming that binding is the primary function of the hippocampus (e.g., O'Reilly & Rudy, 2001), they found that hippocampal activity was related to extrinsic object-location binding; however, they found that hippocampal activity was not related to intrinsic object-color binding (Piekema, Kessels, Mars, Petersson, & Fernández, 2006; but see Piekema, Fernández, Postma, Hendriks, Wester, & Kessels, 2007). Yet, the effect may have been specifically related to the spatial processing aspect of their extrinsic task rather than the extrinsic binding requirement per se, as the hippocampus is known to play an important role in spatial processing more generally (cf. Burgess, 2002). The authors addressed this concern in a subsequent study looking at non-spatial binding, and found that the hippocampus is active for both within-domain (face-face, house-house) and between-domain (face-house) binding, but more so in the latter case (Piekema, Kessels, Rijpkema, & Fernández, 2009). In a further study (Piekema, Rijpkema, Fernández, & Kessels, 2010), they contrasted intrinsic (object-color), extrinsic (object-location), and inter-item (object-object) binding, and reported that only inter-item binding activated the medial temporal lobe (including the hippocampus). In sum, there is some suggestion that the hippocampus is more strongly related to extrinsic than intrinsic binding, but the evidence is not (yet) entirely convincing.

Our proposal that the intrinsic/extrinsic dimension applies equally to long- and short-term recognition adds to the growing literature that questions the traditionally sharp distinction between separate short- and long-term memory systems. That is, despite some evidence that long-term memory and short-term working memory are subserved by partially independent brain systems (e.g., Izquierdo, Medina, Vianna, Izquierdo, & Barros, 1999), recent work has focused on commonalities between short- and long-term systems (Cashdollar, Duncan, & Düzel, 2011; Neath & Suprenant, 2008; Öztekin, Davachi, & McElree, 2010; Piekema et al., 2006; Ranganath & Blumenfeld, 2005; for a review see Jonides et al., 2008).

Additionally, and going beyond the recognition memory domain, our data (Experiment 4) suggest that what is considered ‘intrinsic’ to an object depends on the way the object is first perceived and processed. These links from short-term working memory to both long-term recognition on the one hand and perception on the other hand make a strong case that the intrinsic-extrinsic dimension is an important principle of human cognition. We now discuss some supporting evidence for this claim.

The link from perception to memory. In perception, G. Humphreys (1998) has proposed that object identification relies on “within-object representations” integrating intrinsic parts of objects (as opposed to “between-object representations” subserving navigation and action). O’Craven, Downing, and Kanwisher (1999) found that attending to one feature of an object enhances the neural representation not only of the attended feature, but also of other features of that object: In this fMRI study, participants viewed transparent and superimposed images of a face and a building, and either the face or the building moved. The task directed subjects’ attention to the face, the building, or the movement. Activity in the brain areas known to process such information (e.g., the fusiform area for face processing) indicated that attending to the movement led to increased activation in the “movement” area *and* the area processing the actual stimulus (e.g., the face), and vice versa, despite all stimuli

occupying the same spatial location. Thus, task-irrelevant features of an attended object will be selected along with task-relevant ones, even when these features are processed by distinct brain structures, and even across modalities (Molholm, Martinez, Shpaner, & Foxe, 2007). This implies that objects are selected by attentional processes in their entirety, and therefore objects (and their intrinsic features) constitute the likely units of both perception and various kinds of memory.

Neuropsychological evidence for a general principle. In this vein, neuropsychological research has suggested that unitization and intrinsicity factors are not only relevant for episodic long-term memory, but various forms of memory. In particular, several lines of research suggest that the pattern of memory deficits experienced in anterograde amnesia—a neuropsychological syndrome caused by hippocampal damage—may be best considered to represent an extrinsic binding deficit rather than a deficit specific to episodic long-term memory (see Curran & Schacter, 1997, for a similar argument).

First, some amnesics still experience feelings of episodic long-term familiarity (presumably involving intrinsic binding) when encountering familiar objects and people, but virtually none can remember contextual specifics of previous encounters (presumably involving extrinsic binding; Baddeley, Vargha-Khadem, & Mishkin, 2001; Düzel, Vargha-Khadem, Heinze, & Mishkin, 2001; Mayes, Holdstock, Isaac, Hunkin, & Roberts, 2002).

Second, while it has been textbook knowledge for a long time, the notion that amnesia affects long-term but not short-term memory is increasingly being challenged. For example, a number of studies have now reported that amnesics are impaired in holding relational information even over the course of a few seconds (Hannula, Tranel, & Cohen, 2006; Olson, Page, Moore, Chatterjee, & Verfaellie, 2006; Olson, Moore, Stark, & Chatterjee, 2006; but see Baddeley, R. Allen, & Vargha-Khadem, 2010; for a review, see Cashdollar et al., 2011).

Likewise, and third, amnesics—who typically demonstrate intact implicit memory—sometimes show severe deficits in implicit memory tasks if these involve contextual binding (Chun & Phelps, 1999; Ryan, Althoff, Whitlow, & Cohen, 2000; Verfaellie, Martin, Page, Parks, & Keane, 2006). In conditioning, animals with hippocampal lesions do not show performance decrements typically found in healthy organisms when conditioned stimuli are presented in novel contexts (M. Allen, Padilla, Myers, & Gluck, 2002; Penick & Solomon, 1991).

Further implications for working memory theory. In line with these neuropsychological findings that highlight commonalities across multiple forms of memory, there is a growing theoretical drive in cognitive science to find time-scale invariant aspects of human memory (cf. Brown et al., 2007). In particular, some recent working memory models argue that working memory operates on activated long-term memory representations (Cowan, 1999; Oberauer, 2002, 2005, 2009). In these models, binding—which has traditionally been regarded as a hallmark of long-term episodic memory—has been directly linked to WM capacity (see in particular Oberauer, 2002, 2005, 2009; see also Oberauer & Lewandowsky, 2008; Lewandowsky & Farrell, 2008). Typical WM tasks involve the storage of items in a particular temporal order (e.g., remembering the correct order of a series of digits) or in a spatial array (e.g., remembering digits in frames, i.e., locations). Thereby, each individual item is associated with a position in time or space. Thus, to maintain an ordered WM representation of a set of items, individual item information (e.g., the digits) needs to be bound to contextual information (e.g., their position in time or space). The limited ability to perform this kind of arbitrary contextual binding likely sets an upper boundary for WM processing and thus performance in many tasks relying on WM. Hence, WM capacity can be understood as binding capacity. The present study, however, shows that intrinsic binding

occurs rather automatically in short-term recognition, hence suggesting that these WM models need to specify the type of binding that relates to WM capacity as extrinsic binding.

To illustrate, Oberauer and colleagues have shown that binding measures do not only predict WM capacity but are also excellent predictors of reasoning abilities and fluid intelligence (Oberauer, 2005; Oberauer, Süß, Wilhelm, & Sander, 2007; Oberauer, Süß, Wilhelm, & Wittmann, 2008; Wilhelm, Hildebrandt, & Oberauer, 2011). They claim that this is why WM capacity itself predicts reasoning and intelligence: Reasoning requires relational integration and the ad-hoc generation of new relational representations, that is, bindings. While they do not explicitly state that only extrinsic binding is important, there is some tentative evidence that these relations between binding measures and intelligence are only obtained with extrinsic but not intrinsic binding measures (Oberauer et al., 2008; R. Allen, personal communication, August 3, 2011). This demonstrates the value of the intrinsic-extrinsic distinction not only for long-term memory but also for WM research and theory.

Conclusion

We presented a series of experiments strongly suggesting that intrinsic but not extrinsic object information is obligatorily bound in visual working memory. We have highlighted links to perception, implicit and explicit long-term memory, as well as reasoning and intelligence, which suggest that the intrinsic-extrinsic dimension is a principle relevant to multiple domains of human cognition.

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Footnotes

¹ Despite the fact that the experiments of the present study are only concerned with short-term memory, and despite the traditional view of separate short- and long-term memory systems, we will argue that the distinction between intrinsic and extrinsic binding applies equally to both short- and long-term memory in terms of a general principle of cognition. In the following, we therefore do not always sharply distinguish between short- and long-term memory studies.

² In this study, intrinsic binding was assessed by the association of words printed in black on colored cards. While color is then clearly an intrinsic feature of the stimulus *card*, it could be considered extrinsic to the *word*. Experiment 4 will address this issue further.

³ We note that Karlsen et al. (2010) did use articulatory suppression tasks during encoding and retention, which may have prevented verbal recoding of their nameable stimuli.

⁴ In principle, this shortcoming of change-detection tasks could be overcome by manipulating a third, task-irrelevant feature (cf. Logie, Brockmole, & Jaswal, 2011). Logie et al. reported that with a retention interval of around 1 sec or more (i.e., within the domain of working memory as opposed to iconic memory), study-test manipulations of irrelevant location or shape did not affect memory for shape-color and location-color conjunctions, respectively. However, changes of irrelevant (intrinsic) color tended to affect memory for shape-location bindings. These results are roughly in line with our hypotheses. The asymmetry in their findings will be further addressed in the discussion of Experiment 1.

⁵ Including these trials did not change the pattern of results.

Tables

Table 1

Recognition Performance in Experiment 1

Test-Task	Stimulus-Type	Condition	Accuracy		RT (ms)	
			Mean	SE	Mean	SE
Color task	Extrinsic	New	.95	.01	755	26
		Recombined	.84	.03	772	27
		Same	.82	.03	763	24
	Intrinsic	New	.94	.01	759	26
		Recombined	.87	.02	758	22
		Same	.87	.03	760	24
Shape task	Extrinsic	New	.80	.02	1030	37
		Recombined	.83	.03	878	31
		Same	.84	.03	862	31
	Intrinsic	New	.83	.02	1033	37
		Recombined	.87	.02	907	31
		Same	.90	.02	848	31

Table 2

Recognition Performance in the Shape Task of Experiment 2 (Intrinsic Stimuli)

Condition	Accuracy		RT (ms)	
	Mean	<i>SE</i>	Mean	<i>SE</i>
New	.88	.02	1145	30
Recombined	.82	.03	1101	32
Same	.86	.02	1049	33

Table 3

Recognition Performance in Experiment 3

Test-Task	Stimulus-Type	Condition	Accuracy		RT (ms)	
			Mean	SE	Mean	SE
Color task	Extrinsic	New	-	-	-	-
		Recombined	.67	.05	856	64
		Same	.70	.03	852	65
	Intrinsic	New	-	-	-	-
		Recombined	.69	.03	888	62
		Same	.77	.03	812	56
Shape task	Extrinsic	New	.78	.02	1003	21
		Recombined	.75	.03	930	16
		Same	.78	.02	920	16
	Intrinsic	New	.77	.03	985	23
		Recombined	.74	.02	947	14
		Same	.84	.02	878	16

Table 4

Recognition Performance in Experiment 4

Test-Task	Presentation/ Instruction	Condition	Accuracy		RT (ms)	
			Mean	SE	Mean	SE
Color task	Separable	New	-	-	-	-
		Recombined	.74	.02	1020	59
		Same	.59	.03	1032	64
	Unitized	New	-	-	-	-
		Recombined	.71	.03	1062	59
		Same	.66	.02	1076	64
Shape task	Separable	New	.73	.03	1039	24
		Recombined	.74	.03	929	20
		Same	.76	.02	916	18
	Unitized	New	.71	.03	1088	23
		Recombined	.75	.02	970	18
		Same	.82	.02	915	12

Figure Captions

Figure 1. Examples of extrinsic and intrinsic study arrays and test items, used in Experiments 1 to 3. *Same* and *recombined* items consist of a studied shape and a studied color, either in an identical repetition (*same*; column 1) or a novel recombination (*recombined*; column 2). The appropriate response for *same* and *recombined* items in both color and shape tasks would be ‘old’. *New* test items in shape task trials (column 3; Experiments 1-3) have a novel, unstudied shape (paired with a studied color); in color task trials (column 4; Experiment 1), *new* test items have a novel, unstudied color (paired with a studied shape). In both cases, the appropriate response would be ‘new’.

Figure 2. Hit reaction time data from the shape recognition task in Experiment 1, across intrinsic and extrinsic stimulus types and identical (*same*) and recombined study-test repetitions. As colour changes were task-irrelevant, the correct response in all conditions was ‘old’. Error bars show within-subject standard errors of the mean.

Figure 3. Accuracy (hit rate) data from the shape recognition task in Experiment 3, across intrinsic and extrinsic stimulus types and identical (*same*) and recombined study-test repetitions. As colour changes were task-irrelevant, the correct response in all conditions was ‘old’. Error bars show within-subject standard errors of the mean.

Figure 4. Hit reaction time data from the shape recognition task in Experiment 3, across intrinsic and extrinsic stimulus types and identical (*same*) and recombined study-test repetitions. As colour changes were task-irrelevant, the correct response in all conditions was ‘old’. Error bars show within-subject standard errors of the mean.

Figure 5. Example of a study array used in the unitized condition of Experiment 4.

Figure 6. Accuracy (hit rate) data from the shape recognition task in Experiment 4, across unitized and separable presentation/instruction conditions and identical (same) and recombined study-test repetitions. As colour changes were task-irrelevant, the correct response in all conditions was 'old'. Error bars show within-subject standard errors of the mean.

Figure 7. Hit reaction time data from the shape recognition task in Experiment 4, across unitized and separable presentation/instruction conditions and identical (same) and recombined study-test repetitions. As colour changes were task-irrelevant, the correct response in all conditions was 'old'. Error bars show within-subject standard errors of the mean.

Figures

Figure 1.

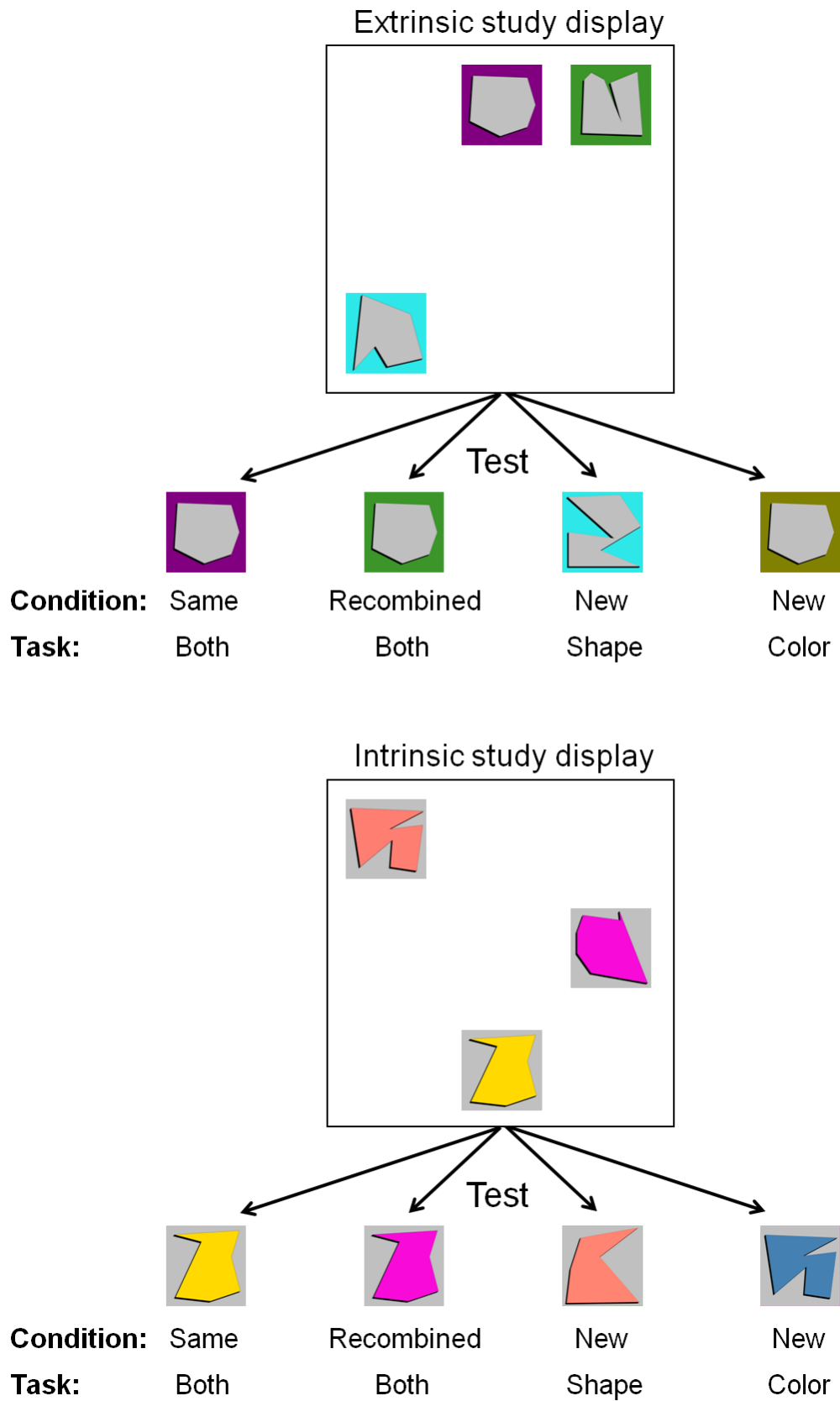


Figure 2.

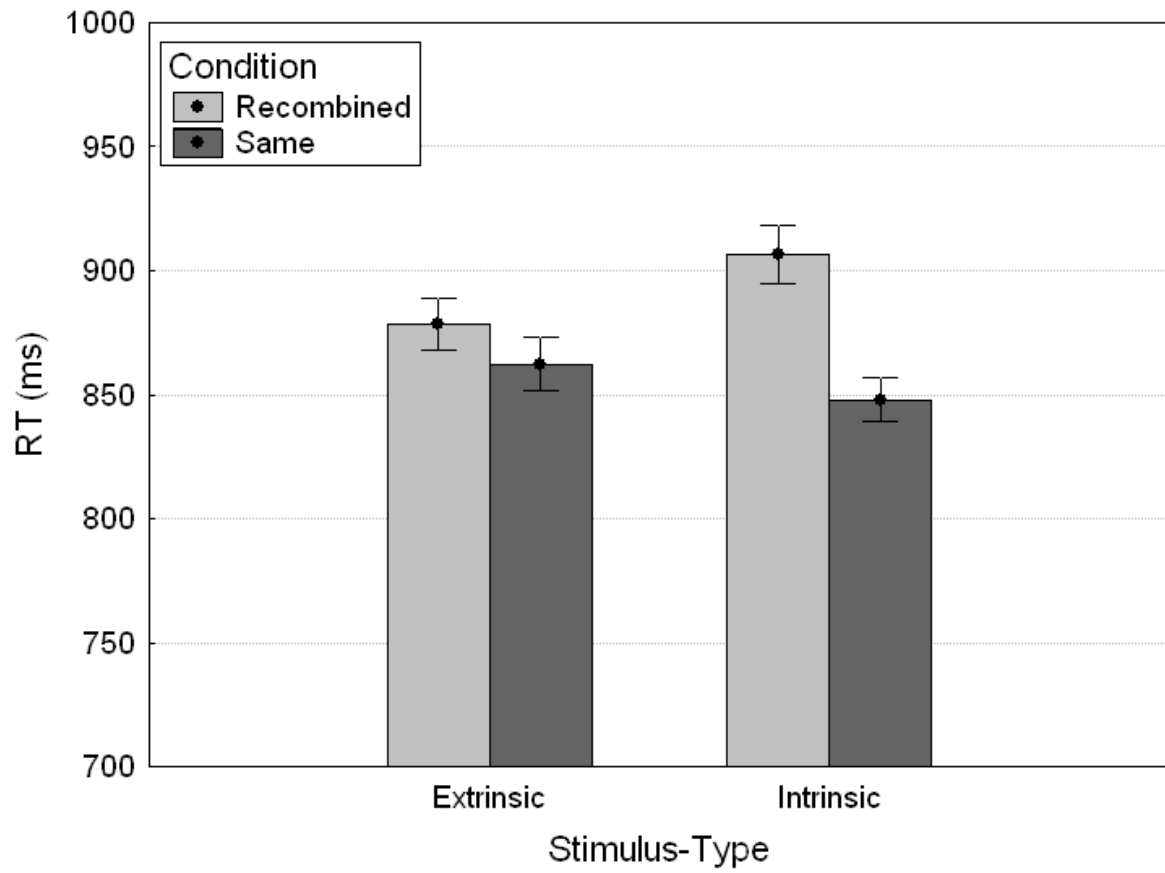


Figure 3.

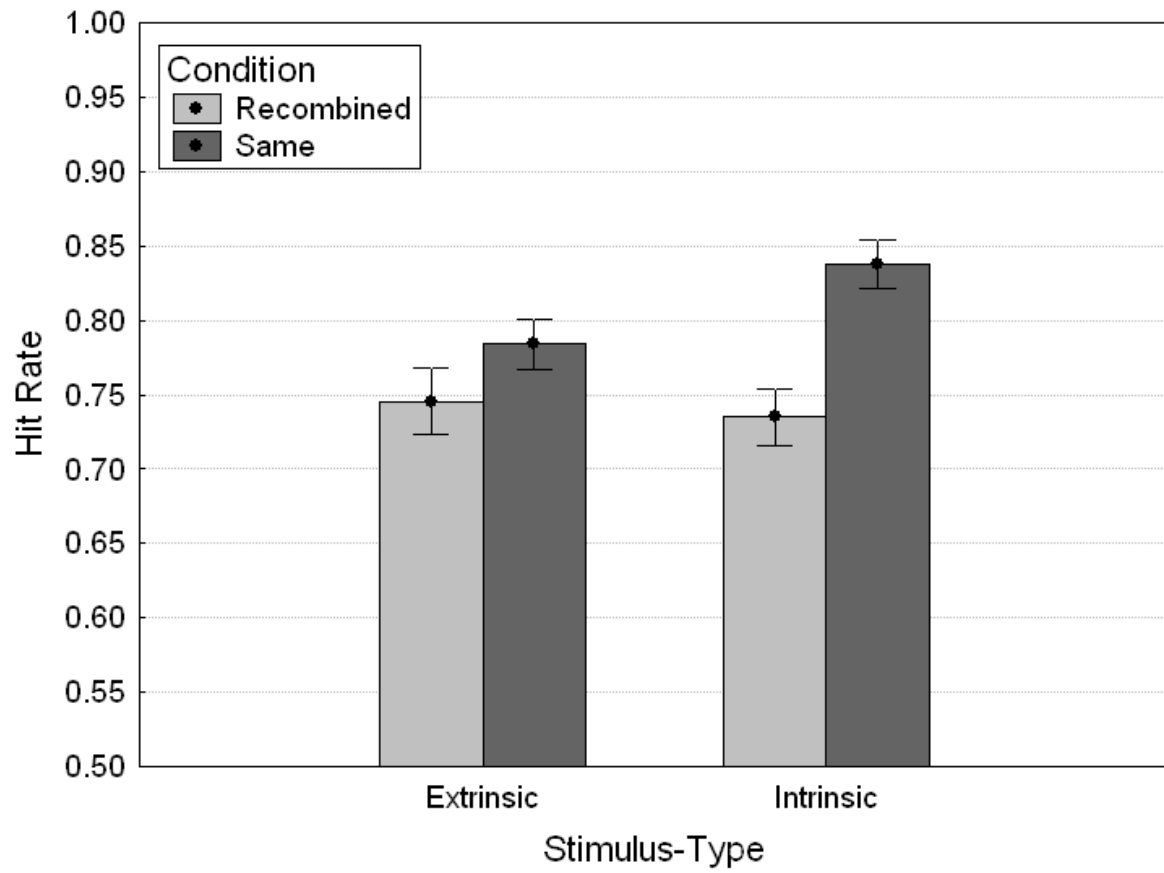


Figure 4.

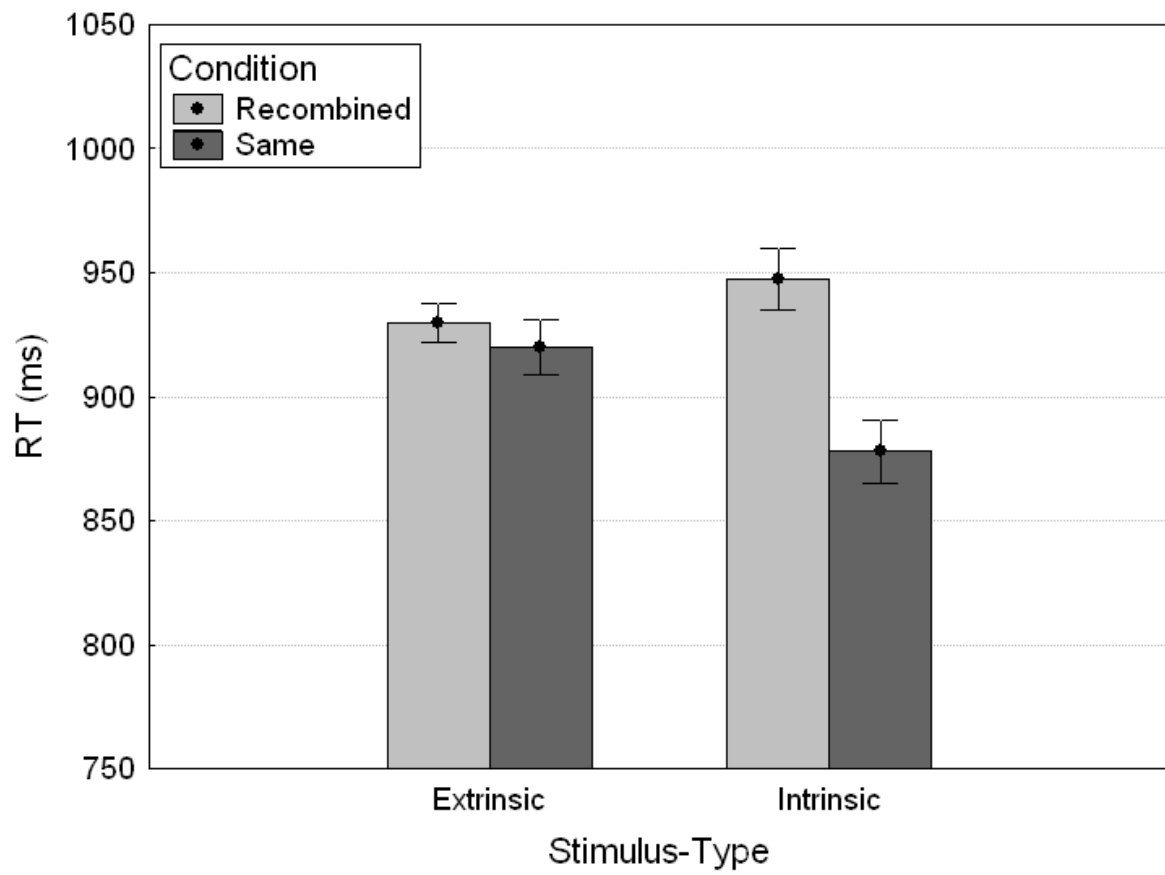


Figure 5.

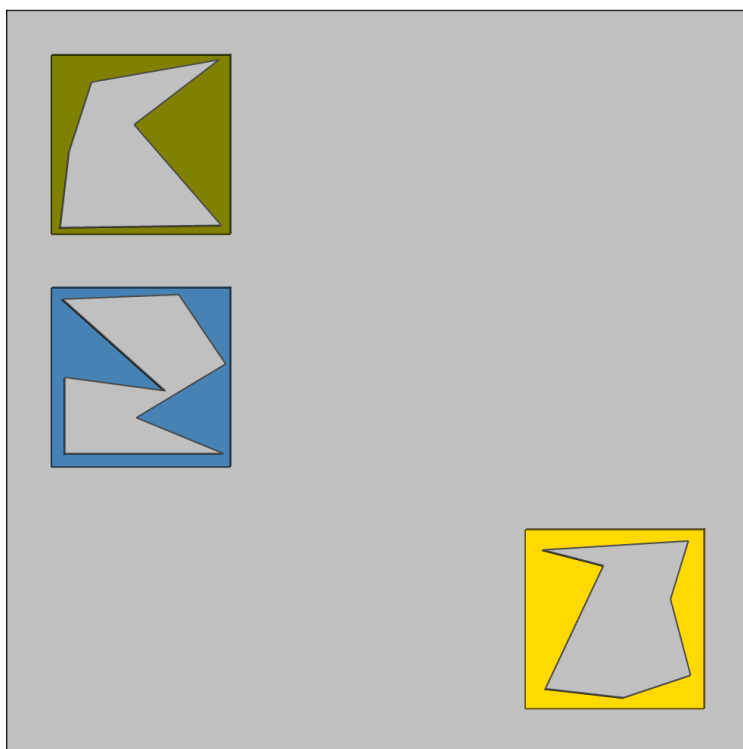


Figure 6.

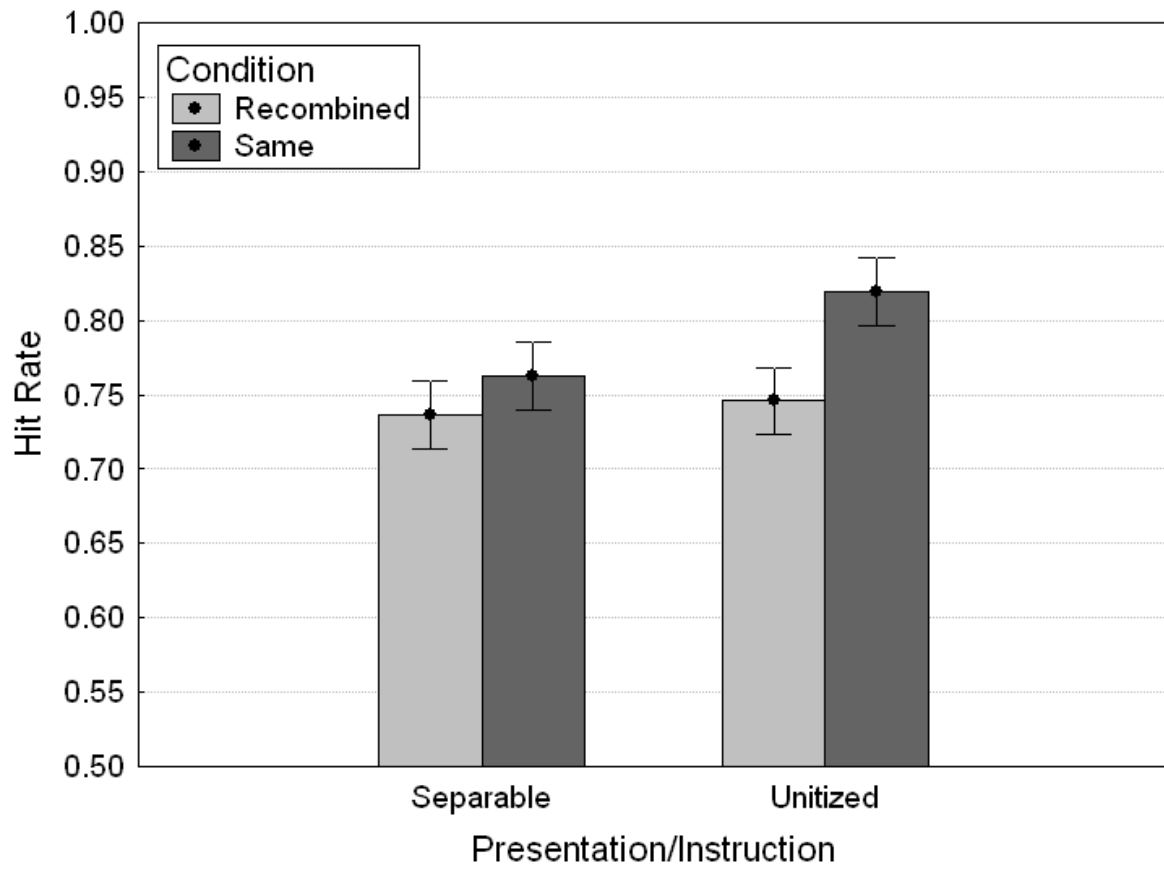


Figure 7.

