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Visual working memory (VWM) is prone to interference from individual items competing for its limited capacity. At least two sources of such interference can be described: poor between-item distinctiveness (an inability to discriminate between items sharing common features) and imperfect binding (a problem with determining which of the remembered features belonged to which object). Here we investigate the links between distinctiveness and binding in VWM. In Experiment 1, we tested how object distinctiveness affects object recognition memory and memory for object-location conjunctions. In Experiment 2, we compared object-location binding under high and low distinctiveness with memory for locations when binding is not required. Object recognition decreased with low object distinctiveness, while the precision and the number of stored locations did not depend on either distinctiveness or the need for binding. However, the proportion of object-location swaps increased as object distinctiveness decreased, which might be caused by forgetting of objects. In general, our data support the idea of relatively independent object and location representations in VWM, and the independence of memory distinction and binding.

JEL Classification: Z

Keywords: visual working memory, distinctiveness, object-location binding, swap errors, binding problem

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Introduction

Working memory is often referred to as a system that actively maintains and operates the information necessary for current goals and tasks (Baddeley, 1986; Baddeley & Hitch, 1974). One of the most important attributes of working memory is its limited capacity (Cowan, 2001; Miller, 1956). Across numerous tasks, modalities and conditions, the average capacity is shown to be about four units (Cowan, 2001). This seems to be true for visual working memory (VWM) as well, a subsystem holding visual information in the working state (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997), though for real-world objects the capacity is not fixed (Brady, Störmer, & Alvarez, 2016; Nickerson, 1965).

Apart from the limited capacity and the limited time of storage, problems can arise from interference between individual items stored in VWM. At least two sources of interference are discussed in the literature. The first is *distinctiveness* (Hunt, 2006), the ability of an item to produce a reliable memory relative to other items or the context. It is usually described and measured as the likelihood of successful recall or the recognition of an item as a function of its similarity or dissimilarity with other memory items. The second source of interference between the items is related to imperfect *binding*. That is, when several items differing in a number of features are stored in memory, it is possible that some features of one item are replaced by the features of a different item.

Distinctiveness in VWM

Early research in this area focused on how the distinctiveness of remembered words influences the verbal memory trace (Conrad, 1964; Baddeley, 1966a; Baddeley, 1966b). The effect of distinctiveness on the VWM capacity has also been studied (Avons & Mason, 1999; Cohen, Konkle, Rhee, Nakayama, & Alvarez, 2014; Jalbert, Saint-Aubin, & Tremblay, 2008). Retrieval decrement in VWM caused by the low distinctiveness of remembered objects was shown for visual patterns in a serial memory task (Avons & Mason, 1999), for information about the time and location of object presentation (Jalbert et al., 2008), for object categories (faces and scenes) using a change detection task (Cohen et al., 2014). Recent studies have shown that the visual distinctiveness of objects in VWM can rely on the separation between neural representations of these objects within the higher levels of the visual cortex, such as the occipito-temporal cortex (Cohen et al., 2014).

However, there are also the data reporting that low object distinctiveness can increase rather than decrease the VWM capacity (Jiang, Lee, Asaad, & Remington, 2016; Lin & Luck, 2009; Sims, Jacobs, & Knill, 2012). Summarizing these contradictory findings, Jiang and colleagues (2016) suggest a possible explanation for this discrepancy. They show that the low-distinctiveness advantage used stimuli with feature variation along a single-type continuum (RGB for color, 360º for orientation, facial morphs, etc.). In contrast, the studies showing the high-distinctiveness advantage have used complex stimuli whose differences are categorical and cannot be presented on a continuum (for example, faces and scenes). Therefore, categorical distinctiveness seems to be an important mediator of VWM capacity.

Binding errors in VWM

The idea that the visual system needs to bind independent features (such as color, orientation, shape, motion, etc.) into the representation of an object comes from studies of perception and attention (Treisman & Gelade, 1980; Wolfe & Cave, 1999). A similar issue is also relevant for VWM. Are the objects stored as bound or unbound entities in VWM? Different studies show that both objects (Kahneman, Treisman, & Gibbs, 1992; Luck & Vogel, 1997; Treisman, 1999) and features (see Brady, Konkle, & Alvarez, 2011, for review; Fougnie, Asplund, & Marois, 2010; Wang et al., 2016; Wheeler & Treisman, 2002) can be the units of VWM. It appears that some resources are needed for keeping bound objects in VWM (Brown & Brockmole, 2010; Fougnie, Asplund, & Marois, 2010; Fougnie & Marois, 2009; Markov & Utochkin, 2016). Some researchers think that the limited capacity of VWM is directly associated with the neurophysiological and biophysical limits of retaining bound representations in the brain (Luck & Vogel, 2013; Raffone & Wolters, 2001).

Binding errors usually take place when correctly perceived or memorized features form false conjunctions that have never been presented. In perception, such errors (often called "illusory conjunctions") can be obtained under special conditions, such as rapid presentation, diverted attention, or inter-object "crowding" (Keele, Cohen, Ivry, Liotti, & Yee, 1988; Prinzmetal, Diedrichsen, & Ivry, 2001; Quinlan, 2003; Treisman & Schmidt, 1982). The illusory conjunctions of object features (such as color and orientation) also exist in VWM (Bays, Wu, & Husain, 2011). However, the most studied type of binding errors in VWM are *object-location* errors, a failure to correctly retrieve both an object and the location of that object.

Object identity and object location seem to be appropriate representational features for studying binding in VWM. The object-location binding problem has a clear neuronal background: information about *what* objects we see and the information about *where* we see these objects are processed by separate pathways of the visual system (Haxby et al., 1991; Mishkin & Ungerleider, 1982). A few behavioral studies (Lee & Chun, 2001; Li, Zhou, Shui, & Shen, 2015; Wood, 2011) showed that memory for objects and memory for locations have separate capacities. There is also neuropsychological evidence for separate capacities (Darling, Della Sala, Logie, & Cantagallo, 2006; Postma, Kessels, & van Asselen, 2008) showing that the medial temporal lobes and in particular the hippocampus play an important role in memory binding (see also Davachi, 2006; Olsen et al., 2015).

Object-location binding errors play an important role in VWM capacity. Bays, Catalao, & Husain (2009) showed that some misreports in VWM tests occur due to binding errors rather than just forgetting, and that the percentage of such binding errors increases with memory set size. The “swap” model suggested by Bays and colleagues (2009) incorporates binding errors as a source of interference in VWM. Pertzov and colleagues (Pertzov, Dong, Peich, & Husain, 2012) suggested that object-location swaps play a central role in delay-related forgetting in VWM. They showed that, while objects themselves are still in VWM, their binding to their correct locations suffers with a delay between encoding and retrieval.

Our study

Although the concepts of distinctiveness and binding imply some feature confusion between memories as a cause of interference, there is one crucial difference between them. The concept of distinctiveness predicts that the more features shared by memory items, the less likely each of the items will be reliably remembered. The idea of binding suggests the opposite. The more shared features the memory items have, the less likely they will produce binding failures, because the common feature is invariant between the items. The contradictory predictions about memory interference following from these two concepts, therefore, require a closer look at them and their possible interaction in VWM.

We ran two experiments to test how object distinctiveness affects memory for objects, memory for locations, and memory for object-location conjunctions. In Experiment 1, we tested recognition memory for low- and high-distinctiveness objects and the ability to recall the locations of such objects. The latter is a critical test of object-location binding. Specifically, we were interested in whether more difficult discrimination between object identities in VWM would affect the precision of their localization and the probability of object-location swaps. In Experiment 2, we compared object-location binding under different levels of distinctiveness with memory for locations under reduced demands on object memory and object-location binding.

Experiment 1

Method

Participants

Nineteen psychology students from the Higher School of Economics (17 female; age: 18-20, M = 19.16) took part in the experiment for extra course credits. All participants reported having normal color vision, normal or corrected to normal visual acuity, and no neurological problems. Before the beginning of the experiment, they signed an informed consent form.

Apparatus and stimuli

Stimulation was developed and presented through PsychoPy (Pierce, 2007) for Linux. Stimuli were presented on a standard VGA monitor with a refresh frequency of 75 Hz and 1024×768-pixel spatial resolution. Stimuli were presented on a homogeneous white field. Participants sat approximately 47 cm from the monitor. From that distance, screen subtended approximately 44.655 × 34.239 degrees of visual angle.

Objects

We used the real-world object database created by Konkle and colleagues (Konkle, Brady, Alvarez, & Oliva, 2010). 200 unique categories and 16 unique exemplars from each category were chosen from the database. Examples of two categories (“apple” and “toy soldier”) and four exemplars are shown on Figure 1. The objects were scaled to subtend approximately 3.62º of visual angle.

Figure 1. Examples of two categories (“apple” and “toy soldier”) and four exemplars from each category

Binding task

Each sample screen contained three objects. The centers of the objects lay on an imaginary circle with a radius of 8.91º. The only parameter defining the position of each object was the rotational angle on an imaginary circle. These angles were chosen randomly for each object in each trial. The only restriction was that the minimum distance between the centers of any two objects was 60º of rotation. This was done to avoid overlap or clustering between the objects.

Procedure

The experiment consisted of two tasks. One task measured recognition memory for objects. The other task measured memory for object-location conjunctions. The order of the tasks was counterbalanced across participants.

Object recognition task

Figure 2A shows the organization of a trial in the object recognition task. Participants were shown three sample objects for two seconds, which they had to memorize. A blank retention interval then followed for one second. On the test display following the retention interval, two objects were presented on the right and on the left. One of the objects was “old”, that is, presented among the three samples; the other object was always “new”. The spatial positions of the new and the old objects were randomized across trials. Observers had to decide which of the objects was old indicating its location. Left and right arrow keys were used for indicating the location of the old object. Feedback was provided after each response regarding response accuracy.

The sample and test objects could have low or high distinctiveness. In the case of low-distinctiveness, all three sample items in a trial were the exemplars drawn from one category; both old and new tested items were also from the same category. In the case of high-distinctiveness, the sample items were drawn from three different categories; the new test item was drawn from a fourth category not shown among the samples. 200 low-distinctiveness and 200 high-distinctiveness trials were presented in total in random order. Each particular object (exemplar from a category) was presented only once during the experiment.

Binding task

As in the recognition task, in each trial observers were shown three low-distinctive or high-distinctive objects for two seconds. The objects were located on the screen in a same way as in the object recognition task. After a one-second retention interval, one of the memorized objects was presented, and the participants had to recall its location on the sample display. To do that, the participants had to drag the object along a positional ring with a mouse (Figure 2B). The initial position of the probed item was at the center of the screen until a first mouse click, which moved the object to imaginary sample location circle. When the location was set, the participants pressed “SPACE” to confirm the response and terminate the trial. After response confirmation, feedback informed the participants how close their response had been to the true object location. The location set by the participant was shown by a red cross centered at the set angle; the true location was shown by the probed object presented at that location (Figure 2).

200 low-distinctiveness and 200 high-distinctiveness trials were presented in total in random order. Although the object categories were the same as those used in the object recognition task, all exemplars were different and did not overlap between the tasks. Both the recognition and the localization tasks were preceded by ten practice trials in order to familiarize participants with the tasks. The objects for practicing trials were drawn from additional object

categories not used in the main parts of the tasks. The total time of the experiment was between 45 and 60 minutes.

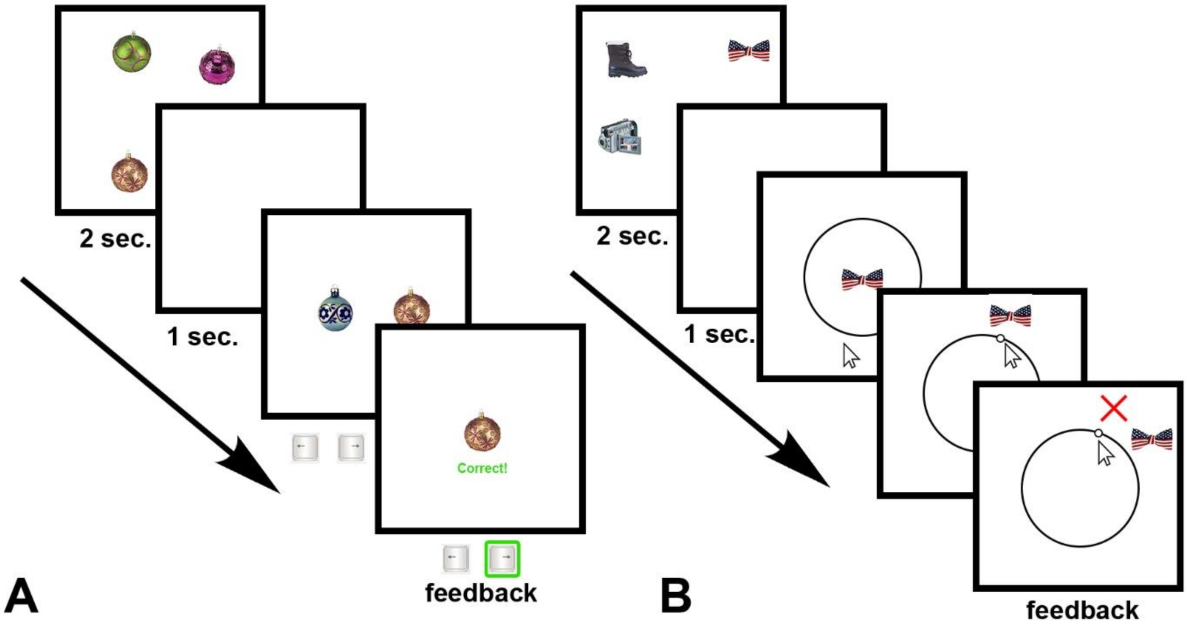

Figure 2. The time course of a trial in (A) recognition task and (B) binding task.

Data analysis

In the recognition task, the percentage of correct recognition was calculated. In the binding task, localization errors were calculated in each trial. The error was estimated as the angular difference between the participant's response and the true location of the probed object. The distribution of errors was then analyzed using the mixture model (Zhang & Luck, 2008) with a modification suggested by Bays and colleagues (Bays et al., 2009), the "swap" model. For modeling, we used MemToolbox for MATLAB (Suchow, Brady, Fougnie, & Alvarez, 2013). The model has three parameters derived from the three decomposed components of the error distribution. The first parameter is the standard deviation (*SD*) of the von Mises distribution built around the mean of 0, which is supposed to reflect responses made about the items whose locations are present in memory with some noise. In representational terms, *SD* estimates the precision of memory trace for the location of a probed item. The second parameter is the probability of random guess (P_{guess}) estimated as an area below the uniform component of the mixed distribution that reflects the random picking of locations in the absence of memory for the location of a probed item. The third parameter is probability of a "swap" (P_{swap}), estimated as the area of a second von Mises component. This second von Mises distribution is assumed to have a mean equaling the location of a distractor item (one of the sample objects that are memorized but not probed) and the same *SD* as the first von Mises distribution. P_{swap} accumulates the responses originating from a misreport of a distractor location instead of a probe location, which is the object-location binding error. Knowing P_{guess} and P_{swap}, it is easy to calculate the probability of correctly bound objects and locations held in VWM (P_{memory}) using the following formula: $P_{memory} = 1 - (P_{guess} + P_{swap})$.

To statistically estimate the effect of distinctiveness on object recognition and object localization, we applied the standard frequentist and Bayesian t-tests to the percentage of correct object recognition, as well as *SD*, P_{memory}, P_{swap}, and P_{guess} of object localization. The Bayesian t-test is a direct way to estimate evidence for H_1 against H_0 (Rouder, Speckman, Sun, Morey, & Iverson, 2009). The Bayes factor (BF_{10}), is the odds between the relative likelihoods of H_1 and H_0 under the observed data, was calculated using JASP 0.8.2 (JASP Team, 2017; Wagenmakers et al., 2017). The Cauchy distribution with a width of .707 was used as a prior distribution of effect sizes under H_0.

Results

In general, the participants were above chance at both remembering the objects (percent correct recognition: M = 95% for high-distinctiveness trials, M = 85.3% for low-distinctiveness trials) and binding them to their location (P_{memory}: M = .935 for high-distinctiveness trials, M = .881 for low distinctiveness trials).

We found that object recognition decreased with low distinctiveness ($t(18) = 13.345$, $p < .001$, $BF_{10} > 10^3$, Cohen's d = 3.062, Figure 3A). A similar effect of distinctiveness was observed on P_{memory} ($t(18) = 8.701$, $p <.001$, $BF_{10} > 10^3$, d = 1.996, Figure 3B). By contrast, low distinctiveness increased P_{swap} (M = .086) compared to high distinctiveness (M = .026; comparison: $t(18) = 8.171$, $p <.001$, $BF_{10} > 10^3$, d = 1.875, Figure 3C). There was no evidence of any effect of distinctiveness on P_{guess} ($t(18) = 1.220$, $p = .238$, $BF_{10} = .348$, d = .28, Figure 3D) and *SD* ($t(18) = .945$, $p = .368$, $BF_{10} = .261$, d = .212, Figure 3E). We concluded, therefore, that low object distinctiveness worsens memory for objects and object-location conjunctions. It does not impair memory for locations themselves in terms of both precision and the probability of remembering the location at all.

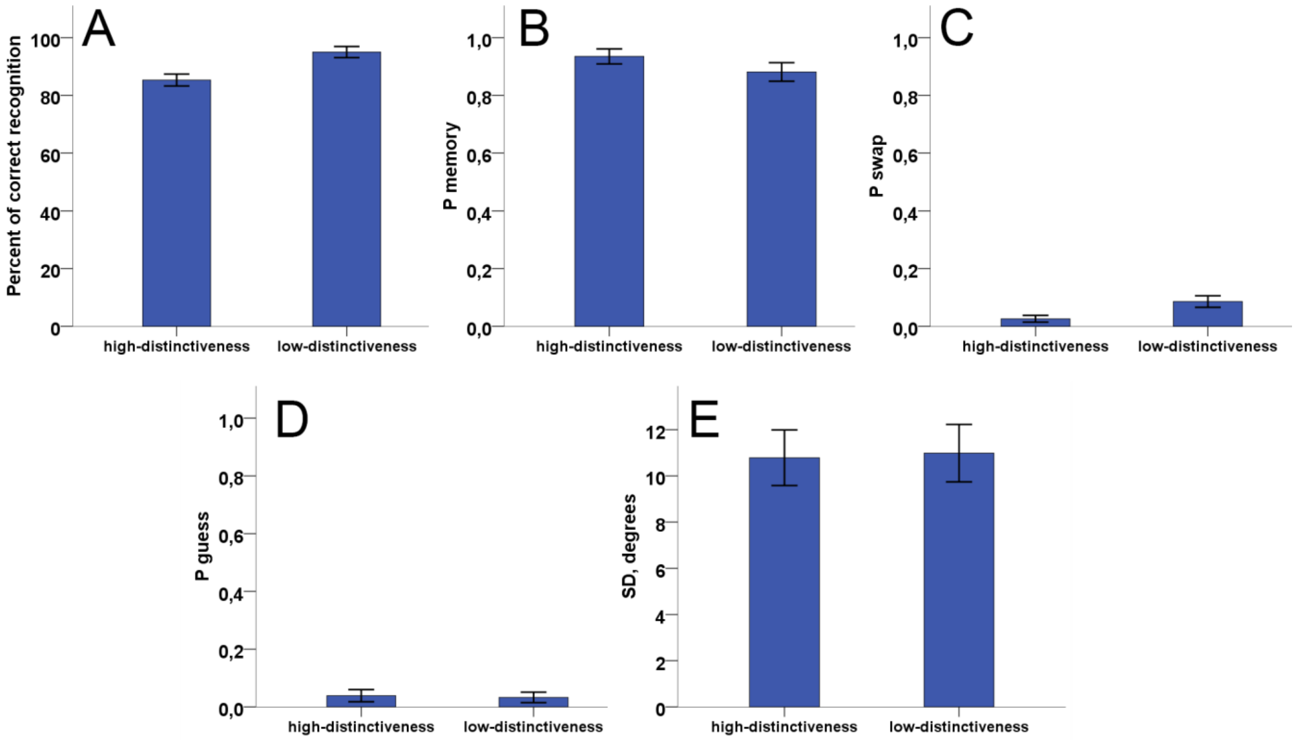

Figure 3. The results of Experiment 1: The effect of distinctiveness on (A) percentage of correct answers in the object recognition task, (B) P_{swap}, (C) P_{memory}, (D) P_{guess} and (E) *SD* in the binding task. Error bars depict 95% CIs.

Experiment 2

Experiment 1 tested object-location binding in the binding task and memory for objects in the object recognition task. The former task requires observers to remember both the objects themselves and where each object was located. The latter task requires only the objects to be remembered, reflecting some “pure” object memory. Experiment 2 tested another source of object-location representation, “pure” memory for locations without objects attached to these locations. We developed a version of the localization task requiring the minimum memory for the objects themselves and for how they are bound to particular locations. We compared this new version of the localization task with the original version used in Experiment 1 (where memory for both the objects and object-location conjunctions are required). As in Experiment 1, we were interested in the effect of object distinctiveness on both location and object-location memories.

Method

Participants

Twenty one psychology students of the Higher School of Economics (19 female; age: 18-21, *M* = 20.07) took part in the experiment for extra course credits. All participants reported having normal color vision, normal or corrected to normal visual acuity, and no neurological problems. Before the beginning of the experiment, they signed an informed consent form.

Apparatus and stimuli

Apparatus and stimuli were the same as in Experiment 1 for the binding task. For the new task, requiring localization without binding, special stimuli were created. We used three pictures of hands depicting numbers from one to three. We used this kind of stimuli instead of showing regular Arabic or Roman numbers, because they looked more like real-world objects and, thus, were more similar to Konkle et al.'s (2010) objects used in the binding task. On each sample display, all three "hand numbers" were located the same way as in the binding task. Additionally, their order was fixed: the "numbers" followed clockwise from "one". We assumed that this sort of display reduced the demands on memory for objects and object-location binding. The reduced demands on object VWM were provided by the fact that the "hand numbers" repeated consistently across the experiment and could be easily learnt during the training session. Moreover, we used the straightforward association between the number of raised fingers and the well-trained numerical representation in long-term memory. The reduced demands on object-location binding was provided by the consistent order of the "hand numbers". It allowed the recovery of the location of any given hand from memory for only one object-location combination. Therefore, by having reduced the uncertainty about object identities and about which locations they belong to, we kept the uncertainty regarding the locations themselves.

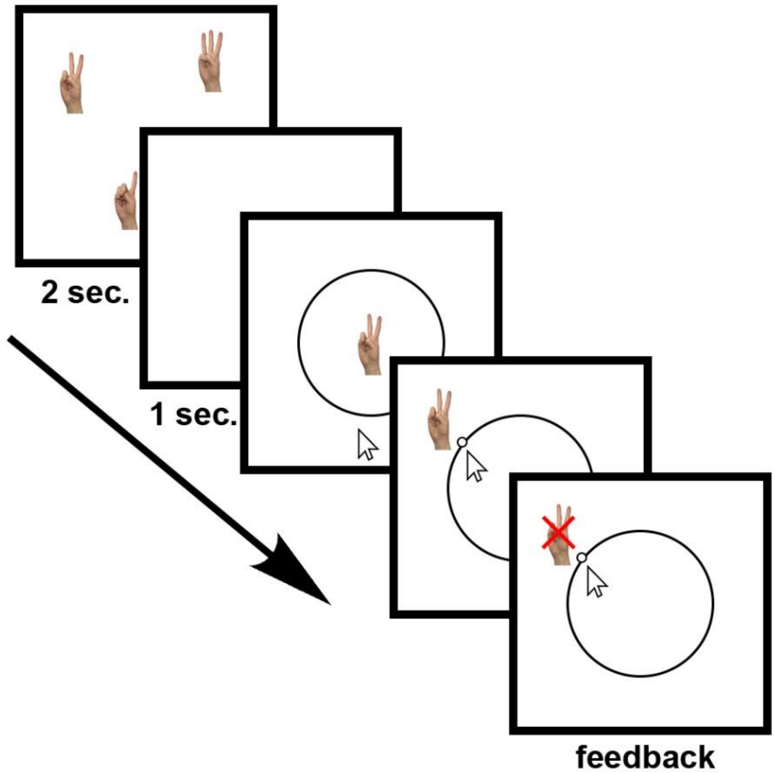

Figure 4. The time course of a trial in the hand localization task.

Procedure

The binding task was exactly the same as in Experiment 1. The hand localization task consisted of 200 trials. The trials were organized the same way as in the binding task: Observers were presented with three "hand numbers" and had to recall the original location of a single probed hand (Figure 4). The order of the object and the hand localization tasks was counterbalanced across participants.

Data analysis

For both the object and the hand localization tasks, we analyzed localization errors using the swap model (Bays et al., 2009), as described in Experiment 1. For each dependent variable (SD, P_{memory}, P_{guess}, P_{swap}), we ran the following planned comparisons. First, compared localization performance between high-distinctive and low-distinctive trials, which was a direct replication of the analysis for the same task in Experiment 1. Second, we compared binding performance (binding task) under each distinctiveness condition with that obtained from the task not requiring binding (the hand localization task). A Holm correction was made for multiple comparisons in calculating the statistical significance level. For Bayesian *t*-tests, the same prior, as in Experiment 1, was used.

Results

The participants were above chance at remembering the locations of the hands (P_{memory}: M = .916) and of object-location conjunctions (P_{memory}: M = .945 for high-distinctiveness trials, M = .888 for low distinctiveness trials).

The results obtained in the binding task of Experiment 1 were very well replicated in Experiment 2. Low object distinctiveness decreased P_{memory} compared to high distinctiveness ($t(20) = 7.317$, $p_{\text{Holm}} =.003$, $BF_{10} > 10^3$, d =1.597, Figure 5A). Symmetrically, low distinctiveness increased P_{swap} (M = .071) compared to high distinctiveness (M = .032; comparison: $t(20)$ = 6.164, $p_{\text{Holm}} =.003$, $BF_{10} > 10^3$, d = 1.345, Figure 5B). Distinctiveness had no effect on P_{guess} (for low distinctive objects M = .041; for high distinctive objects M = .024; comparison: $t(20)$ = 2.030, p_{Holm} = .112, BF_{10} = 1.253, d = .443, Figure) and SD ($t(20)$ = .583, p_{Holm} = .566, BF_{10} = .265, d = .127, Figure 5C).

The comparison between the binding and the hand localization tasks showed no differences for P_{memory} (low-distinctiveness objects vs. "hand numbers": $t(20)$ = 1.599, p_{Holm} = .232, BF_{10} = .68, d = .349; high-distinctiveness objects vs. "hand numbers": $t(20)$ = 1.642, p_{Holm} = .232, BF_{10} = .719, d = .358; Figure 5A) and P_{guess} (low-distinctiveness objects vs. "hand numbers": $t(20)$ = 1.632, p_{Holm} = .112, BF_{10} = .60, d = .356; low-distinctiveness objects vs. "hand numbers": $t(20)$ = 2.336, p_{Holm} = .09, BF_{10} = 1.245, d = .51).

The proportion of swap errors (P_{swap}) in the hand localization task was extremely low (M = .01). This finding demonstrates that our hand localization task was easy in terms of object-location binding and probably can serve a proper tool for measuring spatial memory alone. Proportions of swaps for locating both low-distinctiveness and high-distinctiveness objects were greater than this baseline (low-distinctiveness objects vs. "hand numbers": $t(20) = 5.794$, p_{Holm} = .003, $BF_{10} > 10^3$, $d = 1.264$; high-distinctiveness objects vs. "hand numbers": $t(20) = 2.591$, p_{Holm} = .017, $BF_{10} = 3.179$, $d = .565$; Figure 5B).

For *SD* our results are not completely conclusive, given the difference in the outcomes of statistical analyses using significance tests, effect sizes, and Bayes factors (Wetzels et al., 2011). We found some evidence for a slightly better precision (smaller *SD*) of location memory for hand localization compared to binding from moderate effect sizes and Bayes factors, but it was not significant (low-distinctiveness objects vs. "hand numbers": $t(20) = 2.427$, $p_{\mathrm{Holm}} = .075$, BF_{10} = 2.389, $d = .53$; low-distinctiveness objects vs. "hand numbers": $t(20) = 2.224$, $p_{\mathrm{Holm}} = .076$, $BF_{10} = 1.702$, $d = .485$; Figure 5C). The absolute mean differences between binding *SD* and hand localization *SD* were less than 1º (Figure 5C). We conclude therefore that, even if the differences in precision are present, they are close to negligible.

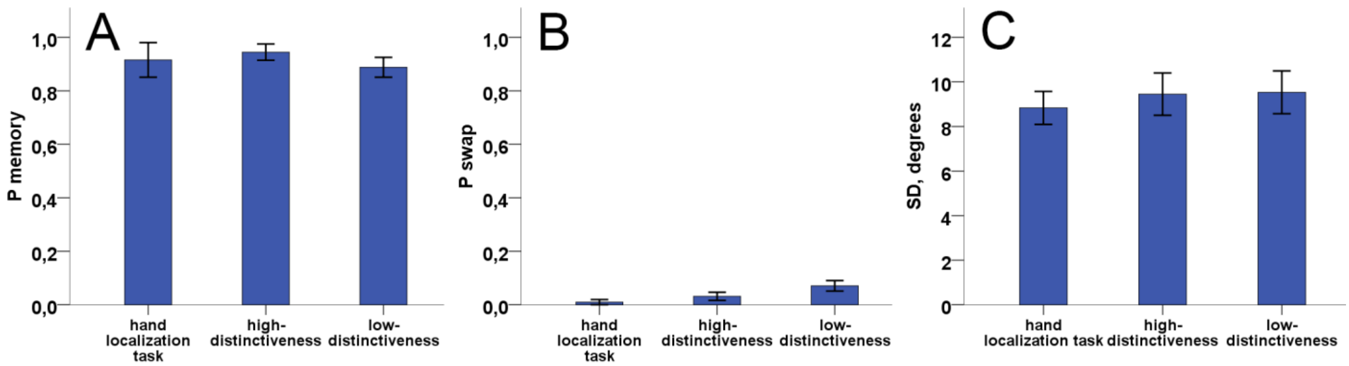

Figure 5. The results of Experiment 2: The effect of distinctiveness on memory parameters in the binding task and parameters of hand localization task ((A) P_{swap}, (B) P_{memory} and (C) *SD*). Error bars depict 95% CIs.

General Discussion

This study tested whether the distinctiveness of objects stored in VWM affects the ability to bind these objects to locations in space. The low distinctiveness of objects provided by the unity of their category increased between-object interference and, hence, encoding difficulty. The results showed that remembering the low-distinctiveness objects was more difficult, as the recognition rate for these objects was lower than for high-distinctiveness objects drawn from different categories. As such, our main question was whether the greater demands on object VWM would also yield poorer memory for the locations of these objects.

In general, spatial memory was good in all conditions of our experiments, as shown by mixture modeling of localization errors (Bays et al., 2009; Zhang & Luck, 2008). More importantly, we found that spatial memory did not suffer substantially from binding. P_{guess} stayed near zero in both the binding task and the hand localization task, showing that binding did not lead to the forgetting of locations. P_{guess} also did not depend on object distinctiveness, suggesting that the demands on object VWM had no effect on location forgetting. In line with these points, we found practically no strong effects of object distinctiveness and binding in general on the precision of spatial memory.

However, we found some interesting results regarding object-location swaps. Although the proportion of these errors was relatively small (as in the previous studies, Bays et al., 2009; Pertzov et al., 2012), it was affected by object distinctiveness. Binding low-distinctiveness objects produced a greater number of swaps. One most obvious explanations for this finding can be that low distinctiveness causes more objects to be forgotten, so observers simply assign random locations to these forgotten objects, which is shown as swap by the swap model. An indirect argument for this explanation is that recognition rates and the probabilities of correct binding (P_{memory}) show quite similar values across the distinctiveness condition (Figures 3A and 3C). On the other hand, the swaps could arise independently from object memory. In line with this, in a similar study, Pertzov et al. (2012) demonstrated that object-location swaps can occur despite almost perfect VWM for objects themselves.

The current design cannot reliably dissociate between the two aforementioned explanations of the effect of distinctiveness on the swap errors. The critical question to be answered here is whether object misidentifications and object-location swaps are the same or at least partly overlapping errors. Future experiments are necessary to clarify this point. A promising approach to accomplish this is combining object recognition and binding tasks within a single trial (as Pertzov et al., 2012, did in their experiments).

The results obtained for all memory parameters are consistent regarding the main research question about the link between distinctiveness and binding as sources of inter-item interference in VWM. The fact that the parameters of object localization in the binding task (precision measure *SD* and capacity measure P_{guess}) are unaffected by distinctiveness suggest that memory distinction and memory binding appear to be independent processes. Although swap errors changed with distinctiveness, the changes do not contradict the idea of independence. If we accept the idea that the swap reports result from object misrecognition, then we should consider these reports a random choice among well stored spatial positions rather than a true binding error. If, by contrast, we accept the idea that swaps are independent of object misrecognition, this directly leads us to the conclusion of the independence between binding and distinction.

Another important question about the effects of distinctiveness on both recognition memory and swaps concerns the format of the affected representation in VWM. One might argue that objects from different categories are remembered better due to easier verbal labeling rather than visual distinctiveness. Indeed, it must be easier to discriminate between three unique categorical names attached to each object than to discriminate between three variants of items having a single categorical name. However, experiments using a concurrent verbal interference task have shown that the effects of visual distinctiveness cannot be explained by verbal coding (Jalbert et al., 2008; Logie, Della Sala, Wynn, & Baddeley, 2000; Poirer, Saint-Aubin, Musselwhite, Mohanadas, & Mahammed, 2007). Moreover, using poorly verbalizable stimuli Pertzov et al., 2012, showed that object-location binding is also not affected by verbal encoding.

In conclusion, it is important to view our data in the broader theoretical context of VWM theories. The two most influential theories regarding the nature of VWM limitations are debated. One says VWM capacity is conceptualized as a fixed number of slots, each containing one bound unit (Luck & Vogel, 1997; 2013; Zhang & Luck, 2008; Lee, & Chun, 2001). The other says VWM capacity is thought to be limited by a continuous resource that can be flexibly divided between objects, so that each individual representation becomes less precise as the number of stored units or their complexity increase (Bays, 2014; Bays, Catalao, & Husain, 2009; Bays, 2015; Bays & Husain, 2008; Wilken & Ma, 2004). We found no evidence for a common resource shared between either object and location memories, or their conjunctions, as the precision of spatial representations was not affected substantially by the binding task or by object distinctiveness. Nor do our data allow us to adopt a strong version of the slot model for object-location binding because location memory was always near perfect, regardless the changes in object recognition rate. A recently stated probabilistic hierarchical theory (Brady & Alvarez, 2011; Brady et al., 2011; Brady & Tenenbaum, 2013; Fougnie & Alvarez, 2011; Fougnie, Asplund, & Marois, 2010) accounts for our data better, as it predicts both independent feature storage at a lower level and bound object storage at a higher level. Our data are in line with independent feature storages for object identities and locations (Darling et al., 2006; Lee & Chun, 2001; Li et al., 2015; Postma et al., 2008; Wood, 2011). Future work on a more rigorous analysis of a possible overlap between object misrecognition and swap errors could also shed light on the links between feature representations and whole object-location representation.

References

Alvarez, G. A., & Cavanagh, P. (2004). The capacity of visual short-term memory is set both by visual information load and by number of objects. *Psychological Science : A Journal of the American Psychological Society / APS*, *15*(2), 106–111. http://doi.org/10.1167/2.7.273

Avons, S. E., & Mason, A. (1999). Effects of visual similarity on serial report and item recognition. *The Quarterly Journal of Experimental Psychology*, (1), 217–240.

Baddeley, A. D. & Hitch, G. J. (1974). Working memory. In G. A. Bower (ed). *The Psychology of Learning and Motivation: Advances in Research and Theory*, pp. 47–89. New York: Academic.

Baddeley, A. D. (1966a) Short-term memory for word sequences as a function of acoustic, semantic and formal similarity. *Quarterly Journal of Experimental Psychology*, 18, 362-365

Baddeley, A. D. (1966b) The influence of acoustic and semantic similarity on long-term memory for word sequences. *Quarterly Journal of Experimental Psychology*, 18, 302-309.

Baddeley, A. D. (1986). *Working memory*. Oxford, UK: Clarendon Press.

Bays, P. M. (2014). Noise in neural populations accounts for errors in working memory. *Journal of Neuroscience*, *34*(10), 3632–3645. http://doi.org/10.1523/JNEUROSCI.3204-13.2014

Bays, P. M. (2015). Spikes not slots: Noise in neural populations limits working memory. *Trends in Cognitive Sciences*, *19*(8), 431–438. http://doi.org/10.1016/j.tics.2015.06.004

Bays, P. M., & Husain, M. (2008). Dynamic shifts of limited working memory resources in human vision. *Science*, *321*(5890), 851–4. http://doi.org/10.1126/science.1158023

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), 7–7. http://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. http://doi.org/10.1016/j.neuropsychologia.2010.12.023

Brady, T. F., & Alvarez, G. A. (2011). Hierarchical encoding in visual working memory: Ensemble statistics bias memory for individual items. *Psychological Science*, *10*(February), 384–392. http://doi.org/10.1177/0956797610397956

Brady, T. F., & Tenenbaum, J. B. (2013). A probabilistic model of visual working memory: Incorporating higher order regularities into working memory capacity estimates. *Psychological Review*, *120*(1), 85–109. http://doi.org/10.1037/a0030779

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. http://doi.org/10.1167/11.5.4

Brady, T. F., Konkle, T., Alvarez, G. a, & Oliva, A. (2013). Real-world objects are not represented as bound units: independent forgetting of different object details from visual memory. *Journal of Experimental Psychology. General*, *142*(3), 791–808. http://doi.org/10.1037/a0029649

Brady, T. F., Störmer, V. S., & Alvarez, G. A. (2016). Working memory is not fixed-capacity: More active storage capacity for real-world objects than for simple stimuli. *Proceedings of the National Academy of Sciences, 113*(27), 7459–7464. http://doi.org/10.1073/pnas.1520027113

Brown, L. A., & Brockmole, J. R. (2010). The role of attention in binding visual features in working memory: Evidence from cognitive ageing. *The Quarterly Journal of Experimental Psychology*, *63*(10), 2067–2079. http://doi.org/10.1080/17470211003721675

Cohen, M. A., Konkle, T., Rhee, J. Y., Nakayama, K., & Alvarez, G. A. (2014). Processing multiple visual objects is limited by overlap in neural channels. *Proceedings of the National Academy of Sciences*, *111*(24), 8955–8960. http://doi.org/10.1073/pnas.1317860111

Cowan, N. (2001). The magical number 4 in short-term memory: a reconsideration of mental storage capacity. *The Behavioral and Brain Sciences*, *24*(1), 87–185. http://doi.org/10.1017/S0140525X01003922

Darling, S., Della Sala, S., Logie, R. H., & Cantagallo, A. (2006). Neuropsychological evidence for separating components of visuo–spatial working memory. *Journal of Neurology*, *253*(2), 176–180. http://doi.org/10.1007/s00415-005-0944-3

Davachi, L. (2006). Item, context and relational episodic encoding in humans. *Current Opinion in Neurobiology*. Elsevier Current Trends. http://doi.org/10.1016/j.conb.2006.10.012

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. http://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. http://doi.org/10.1167/10.12.27

Fougnie, D., & Marois, R. (2009). Attentive tracking disrupts feature binding in visual working memory. *Visual Cognition*, *17*(1–2), 48–66. http://doi.org/10.1080/13506280802281337

Haxby, J. V., Grady, C. L., Horwitz, B., Ungerleider, L. G., Mishkin, M., Carson, R. E., … Rapoport, S. I. (1991). Dissociation of object and spatial visual processing pathways in human extrastriate cortex. *Proceedings of the National Academy of Sciences*, *88*(5), 1621–1625. http://doi.org/10.1073/pnas.88.5.1621

Hunt, R. R. (2006). The concept of distinctiveness in memory research. In *Distinctiveness and memory* (p. 476). Oxford University Press. http://doi.org/10.1093/acprof:oso/9780195169669.003.0001

Jalbert, A., Saint-Aubin, J., & Tremblay, S. (2008). Visual similarity in short-term recall for where and when. *Quarterly Journal of Experimental Psychology (2006)*, *61*(3), 353–60. http://doi.org/10.1080/17470210701634537

JASP Team (2017). JASP (Version 0.8.2) [Computer software]

Jiang, Y. V., Lee, H. J., Asaad, A., & Remington, R. (2016). Similarity effects in visual working memory. *Psychonomic Bulletin & Review*, *23*(2), 476–482. http://doi.org/10.3758/s13423-015-0905-5

Kahneman, D., Treisman, A., & Gibbs, B. J. (1992). The reviewing of object files: object-specific integration of information. *Cognitive Psychology*, *24*(2), 175–219. http://doi.org/10.1016/0010-0285(92)90007-O

Keele, S. W., Cohen, A., Ivry, R., Liotti, M., & Yee, P. (1988). Tests of a temporal theory of attentional binding. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(3), 444–452. http://doi.org/10.1037/0096-1523.14.3.444

Konkle, T., Brady, T. F., Alvarez, G. A., & Oliva, A. (2010). Conceptual distinctiveness supports detailed visual long-term memory for real-world objects. *Journal of Experimental Psychology: General*, *139*(3), 558–578. http://doi.org/10.1037/a0019165

Lee, D., & Chun, M. M. (2001). What are the units of visual short-term memory, objects or spatial locations? *Perception & Psychophysics*, *63*(2), 253–7. http://doi.org/10.3758/BF03194466

Li, J., Zhou, Y., Shui, R., & Shen, M. (2015). Visual working memory for dynamic objects: Impaired binding between object feature and location. *Visual Cognition*, *23*(3), 357–378. http://doi.org/10.1080/13506285.2014.1001010

Lin, P.-H., & Luck, S. J. (2009). The influence of similarity on visual working memory representations. *Visual Cognition*, *17*(3), 356–372. http://doi.org/10.1080/13506280701766313

Logie, R. H., Della Sala, S., Wynn, V., & Baddeley, A. D. (2000). Visual similarity effects in immediate verbal serial recall. *The Quarterly Journal of Experimental Psychology A*, *53*(3), 626–646. http://doi.org/10.1080/027249800410463

Luck, S. J., & Vogel, E. K. (1997). The capacity of visual working memory for features and conjunctions. *Nature*, *390*(6657), 279–81. http://doi.org/10.1038/36846

Luck, S. J., & Vogel, E. K. (2013). Visual working memory capacity: From psychophysics and neurobiology to individual differences. *Trends in Cognitive Sciences*, *17*(8), 391–400. http://doi.org/10.1016/j.tics.2013.06.006

Markov, Y., & Utochkin, I. (2016). The compression of bound features in visual short-term memory. *Journal of Vision*, *16*(12), 1071. http://doi.org/10.1167/16.12.1071

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological Review*, *101*(2), 343–352. http://doi.org/10.1037/h0043158

Mishkin, M., & Ungerleider, L. G. (1982). Contribution of striate inputs to the visuospatial functions of parieto-preoccipital cortex in monkeys. *Behavioural Brain Research*, *6*(1), 57–77. http://doi.org/10.1016/0166-4328(82)90081-X

Nickerson, R. S. (1965). Short-term memory for complex meaningful visual configurations: a demonstration of capacity. *Canadian Journal of Psychology/Revue Canadienne de Psychologie*. Retrieved from http://www.dtic.mil/dtic/tr/fulltext/u2/621592.pdf

Olsen, R. K., Lee, Y., Kube, J., Rosenbaum, R. S., Grady, C. L., Moscovitch, M., & Ryan, J. D. (2015). The role of relational binding in item memory: Evidence from face recognition in a case of developmental amnesia. *The Journal of Neuroscience*, *35*(13), 5342–5350. http://doi.org/10.1523/JNEUROSCI.3987-14.2015

Pertzov, Y., Dong, M. Y., Peich, M. C., & Husain, M. (2012). Forgetting what was where: the fragility of object-location binding. *PLoS ONE*, *7*(10). http://doi.org/10.1371/journal.pone.0048214

Pierce, J. W. (2007). PsychoPy - psychophysics software in Python. *Journal of Neuroscience Methods, 162,* 8-1.

Poirer, M., Saint-Aubin, J., Musselwhite, K., Mohanadas, T., & Mahammed, G. (2007). Visual similarity effects on short-term memory for order: the case of verbally labeled pictorial stimuli. *Memory & Cognition*, *35*(4), 711–723. http://doi.org/10.3758/BF03193309

Postma, A., Kessels, R. P. C., & van Asselen, M. (2008). How the brain remembers and forgets where things are: The neurocognition of object-location memory. *Neuroscience and Biobehavioral Reviews*, *32*(8), 1339–1345. http://doi.org/10.1016/j.neubiorev.2008.05.001

Prinzmetal, W., Diedrichsen, J., & Ivry, R. B. (2001). Illusory conjunctions are alive and well: A reply to Donk (1999). *Journal of Experimental Psychology: Human Perception and Performance*, *27*(3), 538–541. http://doi.org/10.1037//0096-1523.27.3.538

Quinlan, P. T. (2003). Visual feature integration theory: Past, present, and future. *Psychological*

Bulletin, *129*(5), 643–673. http://doi.org/10.1037/0033-2909.129.5.643

Raffone, A., & Wolters, G. (2001). A cortical mechanism for binding in visual working memory. *Journal of Cognitive Neuroscience*, *13*(6), 766–85. http://doi.org/10.1162/08989290152541430

Rouder, J. N., Speckman P. L., Sun D., Morey R. D., & Iverson G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, 16(2), 225-237. doi:10.3758/PBR.16.2.225.

Sims, C. R., Jacobs, R. A., & Knill, D. C. (2012). An ideal observer analysis of visual working memory. *Psychological Review*, *119*(4), 807–30. http://doi.org/10.1037/a0029856

Suchow, J. W., Brady, T. F., Fougnie, D., & Alvarez, G. A. (2013). Modeling visual working memory with the MemToolbox. *Journal of Vision*, *13*(10), 9. http://doi.org/10.1167/13.10.9

Treisman, A. (1999). Solutions to the binding problem: Progress through controversy and convergence. *Neuron*, *24*(1), 105–110. http://doi.org/10.1016/S0896-6273(00)80826-0

Treisman, A., & Gelade, G. (1980). A Feature-Integration of Attention. *Cognitive Psychology*, *136*, 97–136.

Treisman, A., & Schmidt, H. (1982). Illusory conjunctions in the perception of objects. *Cognitive Psychology*, *14*(1), 107–141. http://doi.org/10.1016/0010-0285(82)90006-8

Wagenmakers, E.-J., Love, J., Marsman, M., Jamil, T., Ly, A., Verhagen, J., … Morey, R. D. (2017). Bayesian inference for psychology. Part II: Example applications with JASP. *Psychonomic Bulletin & Review*, 1–19. http://doi.org/10.3758/s13423-017-1323-7

Wang, B., Theeuwes, J., Olivers, C. N. L., & Wang, Z. (2016). Separate capacities for storing different features in visual working memory, *42*(7), 1–11.

Wetzels, R., Matzke, D., Lee, M. D., Rouder, J. N., Iverson, G. J., & Wagenmakers, E.-J. (2011). Statistical evidence in experimental psychology. *Perspectives on Psychological Science*, *6*(3), 291–298. http://doi.org/10.1177/1745691611406923

Wheeler, M. E., & Treisman, A. M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology. General*, *131*(1), 48–64. http://doi.org/10.1037//0096-3445.131.1.48

Wilken, P., & Ma, W. J. (2004). A detection theory account of change detection. *Journal of Vision*, *4*(12), 11–11. http://doi.org/10.1167/4.12.11

Wolfe, J. M., & Cave, K. R. (1999). The psychophysical evidence for a binding problem in human vision. *Neuron*, *24*(1), 11–17. http://doi.org/10.1016/S0896-6273(00)80818-1

Wood, J. N. (2011). When do spatial and visual working memory interact? *Attention, Perception, & Psychophysics*, *73*(2), 420–439. http://doi.org/10.3758/s13414-010-0048-8

Zhang, W., & Luck, S. J. (2008). Discrete fixed-resolution representations in visual working memory. *Nature*, *453*(7192), 233-U13. http://doi.org/Doi 10.1038/Nature06860

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