In Press, *Journal of Experimental Psychology: Learning, Memory, and Cognition*

Semantic and Functional Relationships Among Objects Increase the Capacity of Visual Working Memory

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Visual working memory (VWM) has a limited capacity of approximately 3-4 visual objects. Current theories of VWM propose that a limited pool of resources can be flexibly allocated to objects, allowing them to be represented at varying levels of precision. Factors that influence the allocation of these resources, such as the complexity and perceptual grouping of objects, can thus affect the capacity of VWM. We sought to identify whether semantic and functional relationships between objects could influence the grouping of objects, thereby increasing the functional capacity of VWM. Observers viewed arrays of eight to-be-remembered objects arranged into four pairs. We manipulated both the semantic association and functional interaction between the objects, then probed participants' memory for the arrays. When objects were semantically related, participants' memory for the arrays improved. Participants' memory further improved when semantically related objects were positioned to interact with each other. However, when we increased the spacing between the objects in each pair, the benefits of functional but not semantic relatedness were eliminated. These findings suggest that action-relevant properties of objects can increase the functional capacity of VWM, but only when objects are positioned to directly interact with each other.

Visual working memory (VWM) is a limited capacity resource that allows observers to temporarily store and mentally manipulate up to 3-4 visual objects (Cowan, 2001; Luck & Vogel, 1997). Understanding the factors that underlie this limit has been an important area of research over the past two decades. The first theories to account for the capacity of VWM are broadly referred to as "slot theories." According to these theories, VWM contains a fixed number of independent storage slots, each of which can hold a single object (e.g., Awh, Barton, & Vogel, 2007; Gajewski & Brockmole, 2006; Luck & Vogel, 1997; Zhang & Luck, 2008). Once the available slots are full, additional objects are unable to enter VWM, resulting in memory failures. However, a growing body of evidence suggests that slot theories are too rigid in their conception of VWM capacity, and a newer set of theories referred to as "resource theories" have emerged (see Ma, Husain, & Bays, 2014, for a review).

Although multiple versions have been suggested, resource theories as a class propose that VWM capacity arises from a limited pool of resources that can be flexibly allocated to objects (e.g., Alvarez & Cavanagh, 2004; Franconeri, Alvarez, & Cavanagh, 2013; Gorgoraptis, Catalao, Bays, & Husain, 2011; van den Berg, Shin, Chou, George, & Ma, 2012; Wilken & Ma, 2004). As more resources are allocated to an object, that object can be better represented in VWM. However, as the number of to-be-remembered objects increases, the resources that can be allocated to each one declines, along with the quality with which they can be represented. Thus, according to this view, memory failures occur not because some objects are prevented from entering VWM, but because not all objects can be sufficiently represented to complete a given task (e.g., Schneegans & Bays, 2016). As a result, these theories suggest that the capacity of VWM is not only influenced by the number of objects in a display, but also by other factors that modulate how resources can be allocated to objects. For example, as objects become more visually complex, fewer of them can be remembered, because more complex objects require more resources to be represented (Alvarez &

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Cavanagh, 2004; see also Wheeler & Treisman, 2002; Xu, 2002).

Thus, while VWM has a limited capacity, an emerging view is that this limit is not fixed. Instead, the functional capacity of VWM appears to be flexible based on how resources are used to encode and store visual information. However, the factors that influence the capacity of VWM are not fully understood, in part because the methods that have been used to assess VWM capacity have been rather restricted in their range. The most common approach has been to vary the number or complexity of objects in a to-be-remembered display, and then to test observers' memory for one or more of the objects using change detection, cued recall, or some form of delayed estimation. In each of these cases, objects are generally treated as independent units that have little relationship with each other. Some work has deviated from this trend by showing that statistical covariance among visual features (Brady, Konkle, and Alvarez, 2009) and perceptual grouping principles (Brady & Tenenbaum, 2012; Woodman, Vecera, & Luck, 2003) can increase the capacity of VWM. However, the potential influence of higher-order conceptual regularities such as the semantic or functional relationships among objects remains an open question. This constitutes an important gap in knowledge because objects in real-world scenes often covary with each other in predictable ways. For example, kitchens contain stoves, pots, and glassware, while offices contain desks, computers, and books. Moreover, pots are often located on stoves, while computers are located on desks. While such relationships have been extensively studied with respect to long-term memory (see Hollingworth, 2009 for a review), with little exception (discussed later) VWM research has not addressed the effects of these semantic and functional relationships on our ability to remember visual information. Our goal was to address this shortcoming.

We took as our starting point prior observations that semantic and functional relationships can improve our visual perception of the world. For example, Green and Hummel (2006) asked participants to detect the presence of a target object in two-object displays. Targets were presented alongside distractors that were either semantically related (e.g., a glass and a pitcher) or unrelated to the target (e.g., a glass and a key). Furthermore, distractors were oriented to depict functional or non-functional interactions with the target (e.g., a pitcher pouring into the glass or away from it). Importantly, targets were recognized more accurately when they were presented with a semantically related distractor. Moreover, this benefit increased when distractors were oriented to functionally interact with the target. These results indicate that both semantic and functional relationships lead to the perceptual grouping of objects, which in turn facilitates object recognition (see also Roberts & Humphreys, 2011). Work with neurological patients has also demonstrated a strong link between semantic and functional relationships and perception. Following a unilateral lesion to the temporal-parietal junction, patients can exhibit a deficit known as visual extinction, where the perception of objects in the contralesional visual field is reduced when other objects are present in the ipsilesional visual field. However, this extinction is reduced when the objects in each hemifield are frequently used together (i.e., are semantically related), and even more so when the objects are oriented to interact with each other (i.e., are functionally related; Riddoch et al., 2006).

Collectively, this work suggests that semantic and functional relationships play an important role in the perceptual grouping of objects, which in turn facilitates object recognition. Our question in this paper was whether similar effects can support the conceptual encoding of information in VWM. If, as the object recognition literature suggests, arrays of semantically and functionally related objects require fewer resources to process, these arrays should be more easily represented in VWM, increasing the functional capacity of VWM. That said, the degree to which conceptual knowledge can influence VWM is a matter of current debate. For example, Quinlan and Cohen (2016) compared memory performance for displays where objects were drawn from unique semantic categories to those where objects overlapped in their category membership. They observed no benefit of categorical redundancy, leading them to conclude that VWM is "precategorical" in that it is insulated from conceptual knowledge (see also Wong, Peterson, & Thompson, 2008). In contrast, when Rudner et al. (2016) asked deaf participants to monitor a video stream for the repetition of sign language gestures in an *n*-back task, they performed better for signs with which they were familiar, suggesting that conceptual knowledge can, in fact, increase the functional capacity of VWM.

There are several possible reasons why Quinlan and Cohen (2016) and Rudner et al. (2016) obtained conflicting findings. Perhaps Rudner et al.'s focus on sign language encouraged a form of dual-coding that does not generalize to other circumstances. Perhaps Quinlan and Cohen's choice to randomly position objects made it difficult for participants to become aware of categorical redundancies among objects, or perhaps their task's level of difficulty was insufficient to produce categorical effects (cf., Rudner et al.'s effects were greatest when task difficulty was highest). Our goal was not to test these individual hypotheses, but to use them to guide our search for a link between object relationships and VWM capacity. Therefore, we used a task that does not directly involve language, that positions semantically related objects in a manner more consistent with real-world scenes, and that exceeds the canonical capacity of VWM. If semantic and functional relationships lead to the conceptual grouping of objects under these conditions, the complexity of the display should be reduced, improving memory performance.

Experiment 1

All experiments were conducted with the approval of the University of Notre Dame Institutional Review Board. In Experiment 1, observers viewed eight to-be-remembered objects arranged into four pairs. Following the methods of Green & Hummel (2006), we orthogonally manipulated the semantic and functional relationships between the objects in each pair. Our goal was to determine whether VWM performance is improved when semantic and functional relationships are present in the display.

Method

Participants. In pilot studies using similar methods and sample sizes of 14 participants, our observed power to detect semantic and functional relationships were 64% and 69%, respectively. Based on the observed effect sizes in these studies, a power analysis suggested that increasing our sample size to 20 participants would raise statistical power to over 80%. Thus, we recruited a group of 20 University of Notre Dame undergraduates (17 females; mean age = 19.8 years) who participated for course credit.

Stimuli and Apparatus. Stimuli consisted of 20 black-and-white line drawings of common objects. Stimuli were used to create study displays, which consisted of 8 objects arranged into 4 pairs. We created a total of 40 object pairs by varying the semantic and functional relationships between objects (see Figure 1). Semantic relationships were defined by the identities of the objects within each pair. *Semantically related pairs* included objects that share practical, everyday associations, while *semantically unrelated pairs* included objects that lack a common association. Functional relationships were defined by the objects' spatial configuration within each pair. *Interacting pairs* were oriented so that a functional interaction was depicted, while *non-interacting pairs* were oriented so that a non-functional

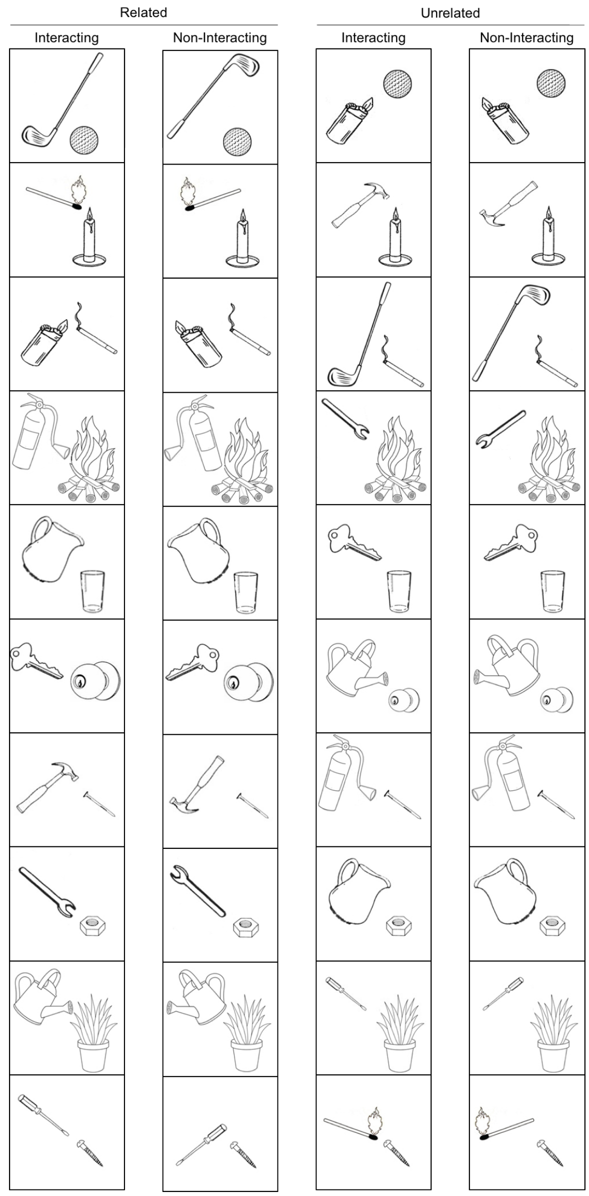

Figure 1. The complete set of object pairs used in Experiments 1 and 2. The candle, cigarette, pitcher, glass, key, hammer, nail, wrench, nut, screwdriver, and were adapted from Snodgrass & Vanderwart (1980) and the rest were created by the authors.

interaction was depicted. Orthogonally combining these semantic and functional relationships yielded four pair types: *related interacting pairs* (Figure 1, first column), *related non-interacting pairs* (Figure 1, second column), *unrelated interacting pairs* (Figure 1, third column), and *unrelated non-interacting pairs* (Figure 1, fourth column). Within each study display, all four object pairs were constrained to be of the same type. Each object pair subtended 200 x 200 pixels, and the four pairs were positioned 200 pixels above, below, left, and right of the center of a 22"

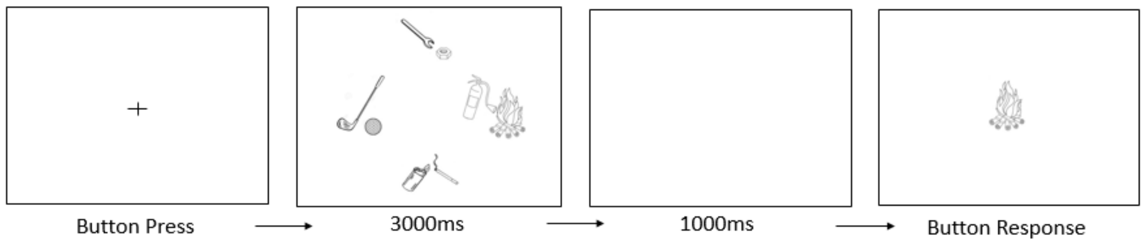

Figure 2. The trial procedure used in Experiment 1. A trial with related interacting pairs is depicted.

display with a resolution of 800 x 600 pixels. Viewing distance was not constrained, and participants' responses were collected using a standard computer keyboard.

Procedure and design. The trial procedure is illustrated in Figure 2. While viewing an initial fixation cross, participants initiated a trial by pressing the spacebar. A study display then appeared for 3000 ms, followed by a blank screen for 1000 ms. Afterward, a single probe object was presented in the center of the screen. Without any time pressure, participants indicated whether this object was present in the previous display by pressing the "z" key for "present" or the "/" key for "absent."

Because a complete counterbalance of object pairs, locations, and probe objects was impractical, on each trial we randomly selected 4 object pairs from the 10 object pairs that were available for each display type, and then randomly assigned each pair to one of 4 locations within the display. For target-present trials, the probe object was randomly selected from the 8 objects that were included in the study display; for target-absent trials, the probe object was randomly selected from the remaining 12 objects. While selecting target-absent probe objects in this manner allowed incidental relationships to exist between the probe object and other items in the study display, any such relationships were unpredictable on a trial-by-trial basis and were randomly distributed across all experimental conditions. Participants completed 40 trials for each combination of semantic relatedness (related, unrelated), functional relatedness (interacting, non-interacting), and response type (present, absent). To reduce the potential of participants using different encoding or retention strategies across conditions, all 320 trials were randomly intermixed within a single block.

Results

Accuracy. Hit and false alarm rates for each condition are presented in Table 1. Memory accuracy was analyzed in terms of d', a measure of detection sensitivity that is independent of response bias (Green & Swets, 1966; see Figure 3a). A 2 (semantic relatedness: related, unrelated) x 2 (functional relatedness: interacting, non-interacting) repeated measures analysis of variance (ANOVA) revealed a main effect of semantic relatedness, $F(1,19) = 39.0$, $p < .001$, $\eta_p^2 = .67$, with better memory performance on related trials ($M = 1.84$, $SD = 0.68$) than on unrelated trials ($M = 1.01$, $SD = 0.42$). We also observed a main effect of functional relatedness, $F(1,20) = 4.73$, $p = .04$, $\eta_p^2 = .20$, with better memory performance on interacting trials ($M = 1.50$, $SD = 0.51$) than on non-interacting trials ($M = 1.35$, $SD = 0.59$). Importantly, these factors interacted, $F(1,19) = 17.3$, $p < .001$, $\eta_p^2 = .48$. Post-hoc pairwise comparisons

Table 1. Mean hit and false alarm rates (with standard deviations) by semantic and functional relatedness.

	Semantically Related		Semantically Unrelated	
	Interacting	Non-Interacting	Interacting	Non-Interacting
Experiment 1				
Hit	.84 (.10)	.77(.14)	.64(.10)	.65(.15)
FA	.18(.08)	.22(.10)	.29 (.08)	.26(.12)
Experiment 2				
Hit	.74(.09)	.75(.12)	.62(.13)	.67(.14)
FA	.17(.10)	.20(.10)	.29(.12)	.22(.10)

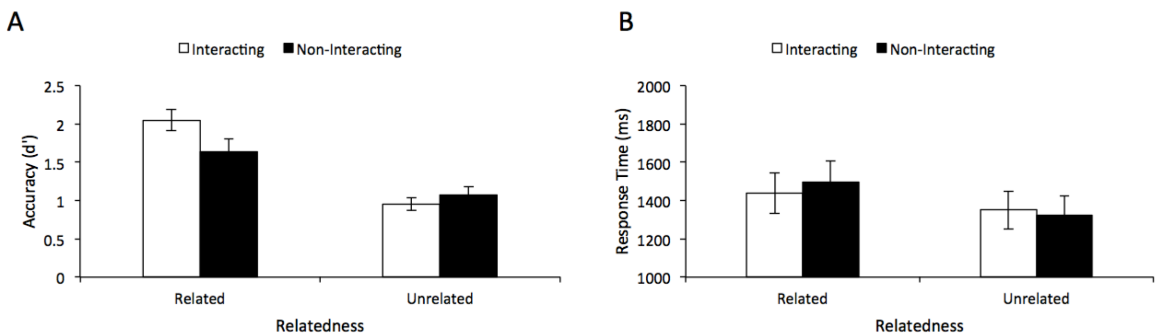

Figure 3. Results of Experiment 1. (A) Memory performance as measured by *d'*. (B) Response time (ms) for correct trials. Error bars in both panels reflect ±1 standard error.

revealed better performance for related interacting pairs (M = 2.05, SD = 0.65) than for related non-interacting pairs (M = 1.64, SD = 0.71), $t(19) = 4.62$, $p < .001$, $\eta_p^2 = .53$. As is apparent from Table 1, this improved memory performance was driven by both an increase in hits ($p < .01$) and a decrease in false alarms ($p = .03$). In contrast, no effect of functional relatedness was observed on semantically unrelated trials, $t(19) = 1.21$, $p = .24$, $\eta_p^2 = .07$, with both hits ($p = .69$) and false alarms ($p = .28$) unaffected by functional relatedness.

Response time. Although our task instructions stressed accuracy and not speed, response times can provide some insight into the ease with which memory representations can be accessed and retrieved. Response time analyses were limited to correct trials (see Figure 3b). A 2 (semantic relatedness) x 2 (functional relatedness) repeated measures ANOVA revealed a main effect of semantic relatedness, $F(1,19) = 5.06$, $p = .036$, $\eta_p^2 = .21$, with participants responding slower on related trials (M = 1467 ms, SD = 492 ms) than on unrelated trials (M = 1337 ms, SD = 441 ms). The main effect of functional relatedness was not statistically reliable, $F(1,19) = 0.32$, $p = .58$, $\eta_p^2 = .02$, and the factors did not interact, $F(1,19) = 1.53$, $p = .23$, $\eta_p^2 = .08$.

Discussion

Both semantic relatedness and object functionality had a positive impact on accuracy. However, the effects of functionality were dependent on the semantic relationship between objects. Functional relationships only improved memory for semantically related pairs, suggesting that action-relevant properties of objects only benefit VWM when those objects share common associations. However, the benefits of semantic relatedness were also associated with costs in response time. As is common in working memory tasks, increasing the contents of VWM often slows responses because additional time is needed to search the contents of the store (e.g., Sternberg, 1966). In contrast to perceptual grouping, which often leads to speeded responses, grouping objects according to their semantic associations in VWM likely slowed responses because doing so resulted in more objects being stored.

Experiment 2

The results of Experiment 1 suggest that both semantic and functional relationships can increase the functional capacity of VWM. In Experiment 2, we sought additional evidence that functional relationships can influence the encoding of objects in VWM. Specifically, we attempted to reduce the functional relationships between objects by increasing the spacing between the objects in each pair. As a result, the objects were no longer positioned to directly interact with each other. If functional relationships benefit the capacity of VWM, these benefits should be reduced or eliminated in Experiment 2.

Method

Participants. Mirroring our sample size in Experiment 1, a new group of 20 University of Notre Dame undergraduates (11 females; mean age = 19.9 years) participated for course credit.

Apparatus and stimuli. The stimuli were the same as in Experiment 1, with one exception. To increase the spacing between the objects in each pair, the horizontal distance between objects was increased so that each pair subtended 400 x 200 pixels. As a

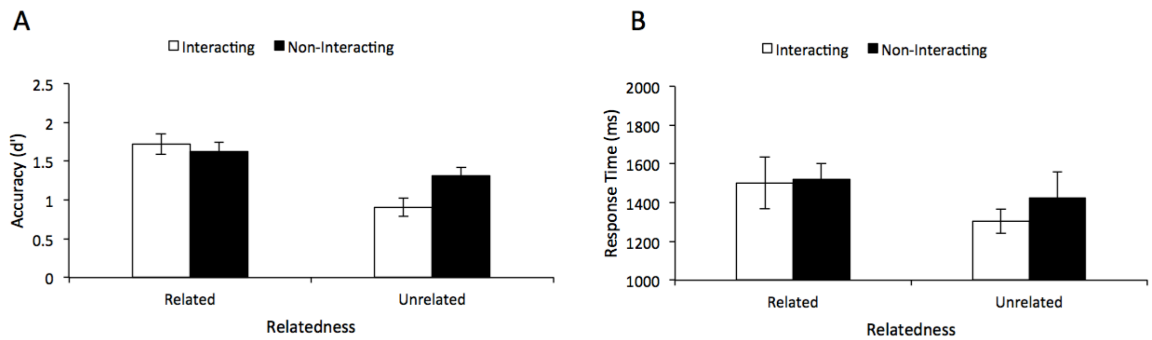

Figure 4. Results of Experiment 2. (A) Memory performance as measured by *d'*. (B) Response time (ms) for correct trials. Error bars in both panels reflect ±1 standard error.

result of this manipulation, objects within adjacent pairs moved closer together. To account for this shift, and to avoid any incidental grouping of objects across pairs, we repositioned the pairs so that they were positioned 200 pixels above and below the center of the display and 280 pixels to the left and right of center.

Procedure and design. The procedure and design were the same as in Experiment 1.

Results

Accuracy. Hit and false alarm rates for each condition are presented in Table 1. As in Experiment 1, memory accuracy was analyzed in terms of *d'* (see Figure 4a). A 2 (semantic relatedness) x 2 (functional relatedness) repeated measures ANOVA revealed a main effect of semantic relatedness, $F(1,19) = 28.6$, $p < .001$, $\eta_p^2 = .60$, with better memory performance on related trials ($M = 1.67$, $SD = 0.56$) than on unrelated trials ($M = 1.11$, $SD = .051$). We also observed a marginal main effect of functional relatedness, $F(1,19) = 3.19$, $p = .09$, $\eta_p^2 = .14$, suggesting better overall memory performance on non-interacting trials ($M = 1.47$, $SD = 0.52$) than on interacting trials ($M = 1.32$, $SD = 0.55$). However, these factors interacted, $F(1,19) = 14.1$, $p < .001$, $\eta_p^2 = .43$. This interaction was explored using post-hoc pairwise comparisons.

Within semantically related trials, no effect of functional relatedness was observed $t(19) = 1.23$, $p = .23$, $\eta_p^2 = .07$, with neither hits ($p = .71$) nor false alarms ($p = .09$) varying across conditions. This finding contrasts with Experiment 1, where an effect of functional relatedness was apparent on semantically related trials. This difference in behavior across experiments was verified by a reliable interaction within a 2 (experiment) x 2 (functional relatedness) ANOVA contrasting performance within semantically related trials, $F(1, 38) = 6.29$, $p = .02$, $\eta_p^2 = .14$. While it is possible that a small effect of functional relatedness escaped detection in Experiment 2, this result nevertheless allows us to conclude that increasing the spacing between objects at least reduces the effect of functional relatedness within semantically related pairs.

Interestingly, within semantically unrelated trials, we observed an unexpected effect of functional relatedness, $t(19) = 3.16$, $p < .01$, $\eta_p^2 = .35$, with better memory for unrelated non-interacting pairs ($M = 1.32$, $SD = 0.49$) than for unrelated interacting pairs ($M = 0.91$, $SD = 0.53$). This finding appears to be primarily driven by a decrease in false alarms ($p < .01$), although a modest increase in hits ($p = .09$) may have also contributed to better memory performance in the non-interacting condition. This contrasts with Experiment 1, where no statistically reliable effect of functional relatedness was observed for semantically unrelated trials. A 2 (experiment) x 2 (functional relatedness) ANOVA contrasting performance within semantically unrelated trials revealed only a marginal interaction between these factors, $F(1, 38) = 3.26$, $p = .08$, $\eta_p^2 = .08$, however, suggesting that the effect may not be isolated to the situation tested in Experiment 2. Because this effect was not predicted, we are cautious with our interpretation. That said, we hypothesize that it may have arisen because participants attempted to interpret the unfamiliar functional interactions depicted among the semantically unrelated objects—a process which may have depleted VWM resources and reduced memory performance. In contrast, situations where semantically unrelated objects did not interact would not lead participants to attempt to reconcile differences between the depicted and usual functions of the objects.

Response time. Response times (see Figure 4b) were analyzed using a 2 (semantic relatedness) x 2 (functional relatedness) repeated measures ANOVA. We observed a main effect of semantic relatedness, $F(1,19) = 17.5$, $p < .001$, $\eta_p^2 = .48$, with participants responding slower on related trials ($M = 1511$ ms, $SD = 486$ ms) than on unrelated trials ($M = 1364$ ms, $SD = 446$ ms). The main effect of functional relatedness was also statistically reliable, $F(1,19) = 9.31$, $p < .01$, $\eta_p^2 = .33$, with participants responding slower on non-interacting trials ($M = 1471$ ms, $SD = 494$ ms) than on interacting trials ($M = 1403$ ms, $SD = 438$ ms). These factors did not interact, $F(1,19) = .23$, p = .64, $\eta_p^2 = .01$.

Discussion

Increasing the spacing between the objects in each pair eliminated the effect of functional but not semantic relatedness. Thus, for object functionality to improve memory for semantically related object pairs, the objects must be positioned to directly interact with each other. As in Experiment 1, better memory performance was associated with slower response times, which is consistent with the notion that as more objects enter VWM, additional time is needed to search the contents of the store (Sternberg, 1966).

General Discussion

A long line of research has demonstrated that the amount of verbal information that can be stored in the working memory system varies according its content. For example, the length (e.g., Baddeley, Thompson, & Buchanan, 1975), frequency (e.g., Roodenrys, Hulme, Alban, Ellis, & Brown, 1994), meaning (e.g., Hulme, Maughan, & Brown, 1991), and organization (e.g., Miller, 1956) of words can all affect measures of memory span as these factors modulate the resources needed to encode verbal material. Indeed, active control processes such as recoding and chunking have long been known to be effective at reducing the storage demands of to-be-remembered information. In contrast, less is known about the flexibility of VWM and how both perceptual and cognitive factors influence its capacity.

Although early theories of VWM capacity likened the store to a series of independent storage "slots" that are rigidly filled as objects enter memory, there is growing evidence that VWM is governed by a limited pool of resources that can be flexibly allocated to objects. Within this conception of VWM, important questions remain about how flexibly these resources can be used to influence the capacity of VWM, as well as which factors modulate the allocation of these resources. In the present study, we investigated whether relationships among objects affect observers' ability to store information in VWM. Specifically, we considered the effects of semantic and functional relationships, which are known to facilitate object recognition. In the present study, we asked whether these relationships can increase the functional capacity of VWM by conceptually linking to-be-remembered objects in memory.

In two experiments, observers were shown arrays of eight to-be-remembered objects. By arranging the objects into pairs, we manipulated both the semantic and functional relationships between objects. In Experiment 1, we demonstrated that memory for the arrays was better when the objects were semantically related than when they were semantically unrelated. Furthermore, among semantically related objects, objects that were depicted to be functionally interacting with each other were remembered better than objects that were not functionally interacting. Because this effect of functionality only occurred when objects were semantically related to each other, action-related properties of objects only appear to benefit VWM when objects share practical, everyday associations. In Experiment 2, we separated the objects in each pair so that direct interactions were no longer depicted. This separation led to an overall decrease in memory performance, as well as a decreased effect of functional but not semantic relatedness. These findings suggest that, as in perception (Green & Hummel, 2006; Riddoch et al., 2006; Roberts & Humphreys, 2011), semantic relationships among objects can serve as a means to conceptually group objects in VWM, and that additive effects of functionality can be observed when objects share common associations.

Overall, the present findings have several consequences for theories of VWM. First, our results suggest that conceptual knowledge can influence representations in VWM. While conceptual knowledge has been shown to modulate visual acuity (e.g., Lupyan, 2017), object recognition (e.g., Green & Hummel, 2006), and attentional control (e.g., Brockmole & Võ, 2009), the relationship between knowledge and working memory has been more equivocal. Some research has suggested that VWM is insulated from long-term memory functions such as conceptual knowledge (Quinlan & Cohen, 2016; see Wong et al., 2008, for a possible exception in the case of faces) and associative learning (Olson & Jiang, 2004). Other research suggests that conceptual knowledge can enhance VWM capacity, at least in visuospatial tasks such as sign language that explicitly rely on semantic processing (Rudner et al., 2016). Although additional work is needed to clarify the role of knowledge in VWM, our results suggest that conceptual knowledge can influence VWM capacity, at least in tasks that do not explicitly involve language and that exceed the canonical capacity of VWM.

Second, viewed through the lens of resource theories, our results suggest that arrays of semantically and functionally related objects require fewer representational resources to process, allowing them to be more easily represented in VWM. Why might semantically and functionally related objects require fewer resources? One mechanism proposed by Brady et al. (2009) provides an elegant answer. In their study, participants were asked to remember the colors of 4 two-colored objects (two concentric circles with different inner and outer colors). In one condition, the colors were randomly assigned to each object; in another condition, some colors were more likely to co-occur in a particular spatial configuration. When the visual features of objects were correlated, memory for the displays improved. The authors linked this result to information compression, whereby redundancies in input reduce storage demands. When information is correlated, each bit of data limits the likely possibilities for the remaining bits and, from a computational point of view, allows more items to be stored in less space. If we view semantic and functional relationships as redundancies that have been learned over a lifetime of experience, they may compress information in a similar manner. For example, semantic relationships may limit the number of objects that are likely to be present in a scene, while functional relationships may limit the number of possible arrangements of those objects. By compressing information in this manner, fewer resources may be needed to encode objects, increasing the functional capacity of VWM.

Third, by addressing questions of both object functionality and semantic relationships, we were able to address the degree to which action-relevant properties of objects influence VWM capacity independently of the effects of semantic relatedness. In the present study, the effects of semantic relatedness and functionality were additive, but only when objects shared common associations. This suggests that object functionality may only provide redundancy in VWM encoding when semantic relationships have been conceptually established. As a result, our findings open new doors for future VWM research, which, in terms of object functionality, has been limited to considerations of motor affordances—the actions that individual observers could take to interact with objects. In contrast to our results, motor affordances appear to have no impact on VWM performance (Pecher, 2013).

Lastly, the results of the present study add to a substantial body of literature on object and scene processing. As a variety of research demonstrates, scene context plays an important role in the perception of objects. For example, objects are recognized more accurately when they are presented within a semantically consistent scene (e.g., Biederman, Mezzanote, & Rabinowitz, 1982; Davenport & Potter, 2004; Palmer, 1975), or when their spatial position is consistent with the overall scene context (Oliva & Torralba, 2007). Scene context also contributes to object memory, with objects being remembered more accurately when they are presented at consistent spatial locations within a scene (Hollingworth, 2006, 2007). In the present study, both semantic and functional relationships between objects improved object memory, even in the absence of a broader scene context. This suggests a local grouping mechanism by which observers can remember objects in real-world scenes.

In conclusion, both semantic and functional relationships between objects can flexibly influence the functional capacity of VWM. By enabling the grouping of objects, these relationships can improve memory for multiple objects in VWM. This finding compliments and extends research on the knowledge-based modulation of visual acuity, object recognition, and attentional control, and may help explain how people process and remember scenes so effectively, even when the sheer number of objects in a scene should overwhelm the capacity of VWM.

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, 15*(2), 106-111.

Awh, E., Barton, B. & Vogel, E.K. (2007). Visual working memory represents a fixed number of items regardless of complexity. *Psychological Science, 18*(7), 622-628.

Baddeley, A.D., Thompson, N., & Buchanan, M. (1975). Word length and the structure of short-term memory. *Journal of Verbal Learning and Verbal Behavior, 14,* 575-589

Biederman, I., Mezzanote, R.J., & Rabinowitz, J.C. (1982). Scene perception: Detecting and judging objects undergoing relational violations. *Cognitive Psychology, 14*(2), 143-177.

Brady, T.F., Konkle, T., & Alvarez, G.A. (2009). Compression in visual working memory: Using statistical regularities to form more efficient memory representations. *Journal of Experimental Psychology: General, 138*(4), 487-502.

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.

Brockmole, J.R., & Võ, M.L.-H. (2009). Semantic memory for contextual regularities within and across scene categories: Evidence from eye movements. *Attention, Perception, & Psychophysics, 72*(7), 1803-1813.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*(1), 87–114.

Davenport, J.L., & Potter, M.C. (2004). Scene consistency in object and background perception. *Psychological Science, 15*(8), 559-564.

Franconeri, S.L., Alvarez, G.A. & Cavanagh, P. (2013). Flexible cognitive resources: Competitive content maps for attention and memory. *Trends in Cognitive Sciences, 17*(3), 134-141.

Gajewski, D.A., & Brockmole, J.R. (2006). Feature bindings endure without attention: Evidence from an explicit recall task. *Psychonomic Bulletin & Review, 13*(4), 581-587.

Green, C., & Hummel, J.E. (2006). Familiar interacting object pairs are perceptually grouped. *Journal of Experimental Psychology: Human Perception and Performance, 32*(5), 1107-1119.

Green, D.M., & Swets, J.A. (1966). *Signal detection theory and psychophysics*. New York: Wiley.

Gorgoraptis, N., Catalao, R.F., Bays, P.M. & Husain, M. (2011). Dynamic updating of working memory resources for visual objects. *Journal of Neuroscience, 31*(23), 8502-8511.

Hollingworth, A. (2006). Scene and position specificity in visual memory for objects. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 32*(1), 58-69.

Hollingworth, A. (2007). Object-position binding in visual memory for natural scenes and object arrays. *Journal of Experimental Psychology: Human Perception and Performance, 33*(1), 31-47.

Hollingworth, A., (2009). In J.R. Brockmole (Ed.). *The Visual World in Mem*ory. Hove, England: Psychology Press.

Hulme, C., Maughan, S., & Brown, G.D.A. (1991). Memory for familiar and unfamiliar words: Evidence for a long-term memory contribution to short-term memory span. *Journal of Memory and Language, 30*(6), 685-701.

Luck, S.J., & Vogel, E.K. (1997). The capacity of visual working memory for features and conjunctions. *Nature, 390*(6657), 279-281.

Lupyan, G. (2017). Objective effects of knowledge on visual perception. *Journal of Experimental Psychology: Human Perception and Performance. 43*(4), 794-806.

Ma, W.J., Husain, M., & Bays, P.M. (2014). Changing concepts of working memory. *Nature Neuroscience, 17*(3), 347-356.

Miller, G.A. (1956). The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychological Review, 63*(2), 81-97.

Oliva, A., & Torralba, A. (2007). The role of context in object recognition. *Trends in Cognitive Sciences, 11*(12), 520-527.

Olson, I.R., & Jiang, Y. (2004). Visual short-term memory is not improved by training. *Memory & Cognition, 32*(8), 1326–1332.

Palmer, S.E. (1975). The effects of contextual scenes on the identification of objects. *Memory & Cognition, 3*(5), 519-526.

Pecher, D. (2013). No role for motor affordances in visual working memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(1), 2-13.

Quinlan, P.T., & Cohen, D.J. (2016). The precategorical nature of visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 42*(11), 1694-1712.

Riddoch, M.J., Humphreys, G.W., Hickman, M., Clift, J., Daly, A., & Colin, J. (2006). I can see what you are doing: Action familiarity and affordance promote recovery from extinction. *Cognitive Neuropsychology, 23*(4), 583–605.

Roberts, K.L., & Humphreys, G.W. (2011). Action relations facilitate the identification of briefly-presented objects. *Attention, Perception, & Psychophysics, 73*(2), 597-612.

Roodenrys, S., Hulme, C., Alban, J., Ellis, A.W., & Brown, G.D.A. (1994). Effects of word frequency and age of acquisition on short-term memory span. *Memory & Cognition, 22*(6), 695-701.

Rudner, M., Orfanidou, E., Cardin, V., Capek, C.M., Woll, B., & Ronnberg, J. (2016). Preexisting semantic representation improves working memory performance in the visuospatial domain. *Memory & Cognition, 44*(4), 608-620.

Schneegans, S., & Bays, P.M. (2016). No fixed item limit in visuospatial working memory. *Cortex, 83,* 181-193

Snodgrass, J., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory, 6*(2), 174-215.

Sternberg, S. (1966). High-speed scanning in human memory. *Science*, *153*(3736), 652-654.

van den Berg, R., Shin, H., Chou, W.-C., George, R. & Ma, W.J. (2012). Variability in encoding precision accounts for visual short-term memory limitations. *Proceedings of the National Academy of Sciences, 109*(22), 8780-8785.

Wilken, P. & Ma, W.J. (2004). A detection theory account of change detection. *Journal of Vision, 4*(12), 1120-1135.

Wheeler, M.E., & Treisman, A.M. (2002). Binding in short-term visual memory. *Journal of Experimental Psychology: General*, *131*(1), 48-64.

Woodman G.F., Vecera S.P., Luck S.J. (2003). Perceptual organization influences visual working memory. *Psychonomic Bulletin & Review, 10*(1), 80-87.

Xu, Y. (2002). Limitations of object-based feature encoding in visual short-term memory. *Journal of Experimental Psychology: Human Perception and Performance, 28*(2), 458-468.

Xu Y. (2006). Understanding the object benefit in visual short-term memory: The roles of feature proximity and connectedness. *Perception & Psychophysics, 68*(5), 815-828.

Zhang, W., & Luck, S.J., (2008). Discrete fixed-resolution representations in visual working memory. *Nature, 453*(7192), 233-235.