Do objects in working memory compete with objects in perception?

of each trial by flashing them a few times. Then all objects move randomly for some fixed period of time—typically 5–10 s. When they stop, participants must either indicate which ones were the targets (using a computer mouse) or, in some experiments, must indicate whether a particular object (e.g., one that is flashed at the end of the trial) was a target. Because all the objects

Using a dual-task MOT-Memory method, Fougnie and Marois (2006) asked participants to perform MOT while holding colours and locations of coloured patches in WM and examined the dual-task interference. Participants memorized the colours and locations of briefly presented circles and then performed an MOT task. At the end of each trial, participants responded to the WM task first and then the MOT task. They found that when one tracks more targets, recognition performance is worse, or in other words, fewer objects can be stored. Nevertheless, this effect is disproportional in MOT and WM. When the number of objects being tracked increases by 1, the number of objects that can be stored drops by only 0.5. This drop in WM is also smaller than that caused by a second WM task.

Although there is evidence for some overlap in cognitive resources between the capacity of WM and the number of objects that can be perceptually individuated and tracked this overlap is relatively small. Moreover, at least four lines of analyses suggest that this overlap may only arise under special conditions.

First, object files (objects in WM) and indices (objects selected in perception) carry different type of information. Object files may store various visual and spatial features of objects, such as colour, orientation, and location (Treisman, 2006). In contrast, indices only select and refer to individual objects (Pylyshyn, 2007)—although some writers have proposed 7,(individua)23.3(ted)ratntial6oug67t6tF7ive20dif,ouredicoals-378ryviduaenbein5.1locatio

Third, if there were common cognitive resources for objects in WM and in perception we would expect a general dual-task interference, but many studies have shown that selective interference of perception in WM occurs only when both WM and perception tasks are visual or spatial (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999; Hecker & Mapperson, 1997; Quinn & McConnell, 1996). For example, in Klauer and Zhao's (2004) study, memorizing a Chinese ideograph was impaired by the concurrent task of finding a stationary asterisk among 12 moving asterisks but not by the task of deciding whether a colour belonged to the red family or the blue family. For memorizing a dot location, the interference pattern was the reverse. Also Olivers, Meijer, and Theeuwes (2006) have recently shown the reverse case: Visual WM content interferes with attentional capture in a content-specific manner. There are also many other studies that fail to show a dual-task interference when the nontracking task was not spatial (Alvarez et al., 2005; Leonard & Pylyshyn, 2003).

Fourth, the influence of WM load on perceptual tasks also appears to be confined to tasks that involve spatial properties. Keeping two or four positions in WM during a visual search slows down the search (Oh & Kim, 2004; Woodman & Luck, 2004), whereas retaining four shapes has no influence on the search, although such a visual WM task is difficult (Woodman, Vogel, & Luck, 2001).

Such considerations suggest that objects in WM and objects being tracked in MOT might have no significant resource overlap. It may be that the weak relation or interference, found by Fougnie and Marois (2006) arise because both the WM task and the perception task in these studies involve spatial processing. In the present study, we test this possibility by examining the dual-task interference between WM and MOT when the WM task is nonspatial.

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A visual WM task usually requires maintaining features of several visual items. When location is among the features to be remembered, the task would involve spatial processing. In the present paper, such a task is called a spatial WM task, and a visual WM task for nonspatial features is called a nonspatial WM task. The purpose of Experiment 1 was to compare the dual-task interference between nonspatial WM and MOT with that between spatial WM and MOT. As illustrated in Figure 1, participants were asked to remember colour-shape bindings of coloured patches or colour-location bindings of coloured squares. During the retention interval, they performed an MOT task. Dual-task interferences were estimated as the difference of performances in such tasks and the corresponding single-task baselines.

Colour-shape conjunctions were used as WM material because it would make our results comparable to those of Fougnie and Marois (2006), where similar stimuli were used. In addition it has been shown in many studies that recall and recognition of conjunctions is more difficult (more attentive or resource-demanding) than recall or single features (e.g., Delvenne & Bruyer, 2004; Postma & de Haan, 1996; Wheeler & Treisman, 2002; for counter-arguments, see Brockmole, Parra, Della Sala, & Logie, 2008; Luck & Vogel, 1997; Vogel, Woodman, & Luck, 2001).

If the weak interference, found by Fougnie and Marois (2006), arises because both the WM task and the tracking task involve spatial processing, such interference effects should only be observed in the colour-location was white and the fixation point was a black cross subtending 0.6° in the centre of the screen.

Each item in the WM tasks subtended 1.0°. In the colour-location condition, the sample display consisted of two or four coloured squares. For

- . At the start of a trial, eight identical disks appeared on the screen and three of them flashed for 1500 ms to indicate that they were the targets. Then all disks began to move and kept moving for 4000 ms. When they stopped, one disk expanded to a larger size. On 50% of the trials, this disk was among the three that had flashed (the targets). Participants were required to indicate whether this disk was one of the targets and they then made an unspeeded "yes" or "no" response, respectively by pressing "f" or "j". The probe display would not disappear until a response had been made or 3000 ms had passed.

- . The sample display was presented for 500 ms, followed by a retention period of 9000 ms. Then the probe display was presented and kept visible until response. In the colour-location condition, participants were instructed to memorize the colours and locations of the items in the sample display; in the colour-shape condition, participants were instructed to memorize the colours and shapes of the items. The memory set size was either two or four. On 50% of the trials, the probe item was one of the sample items; on the other 50% of the trials, the probe item was a combination of two sample items. Participants were asked to decide whether the probe item had occurred in the sample display and make an unspeeded "yes" or "no" response respectively by pressing "f" or "j".

During the 9000 ms retention period, a blank screen was displayed in the first 500 ms and then the display was just like that in MOT-only condition except that the probe display lasted for 3000 ms. Participants were told to view the screen but ignore the moving disks.

- . The procedure of WM-MOT resembled that of WM-only. The only difference was that participants were asked to perform MOT during the retention period of WM. After participants had made their response for the MOT task, a blank screen was used to fill up the remaining time of the 9000 ms retention period.

Each trial began with a fixation cross at the centre of the screen for 1000 ms. The intertrial interval was a random value between 2500 and 3500 ms. To prevent the possible phonological rehearsal of visual or spatial information, participants were required to repeat saying "1, 2, 3, 4" in Chinese throughout a trial in all trials.

There were five types of task: (1) MOT-only, (2) colour-location WM-only, (3) colour-location WM-MOT, (4) colour-shape WM-only, and (5) colour-shape WM-MOT. The five tasks were each presented in a block and the latter four were presented with two different WM set size (two or four). Overall there were nine conditions, each of which was repeated 16 times. Trials within a block were randomized for each participant and the sequence of the blocks was counterbalanced across participants. Before each block, there were five practice trials. Each participant completed all the 169 trials in a 50-minute session.

To correct for guessing, effective number of objects tracked ( ) was computed as the measure of MOT performance and number of conjunctions remembered ( ) as the measure of WM performance. The concept of effective number of objects tracked, which was used in Scholl, Pylyshyn, and Feldman (2000), and Pylyshyn and Annan (2006), refers to the number of

material had a significant effect on the dual-task cost of WM, $F(1, 13) = 17.16$, $p < .01$, and that WM material and set size of WM had an interaction, $F(1, 13) = 15.77$, $p < .01$. So we did t-tests separately on each condition to examine whether the dual-task cost in that condition was different from zero. The dual-task costs of WM in the colour-location condition at set size two and four were significantly above zero, $t(13) = 2.83$, $p < .01$, and $t(13) = 4.16$, $p < .01$, respectively, whereas the dual-task costs of WM in the colour-shape condition at set size two and four were not different from zero.

To be sure that the effect of WM material on the dual-task cost of WM was not due to the difference between the baselines of these two kinds of materials, we carried out a 2 (WM material: Colour-location, colour-shape) × 2 (set size of WM: Two, four) repeated measures ANOVA analysis on the number of conjunctions remembered in single-task conditions. The main effect of WM, the main effect of set size of WM, and the interaction were significant, $F(1, 13) = 8.25$, $p = .01$, $F(1, 13) = 8.52$, $p = .01$, and $F(1, 13) = 8.96$, $p = .01$, respectively. A further simple effect analysis showed that memories for colour-location and colour-shape were significantly

$$K_r = \frac{K_{\text{single task}} - K_{\text{dual task}}}{K_{\text{single task}}}$$

Then a 2 (WM material: Colour-location, colour-shape) × 2 (set size of WM: Two, four) repeated measures ANOVA analysis on K_r was conducted. Results showed that the main effect of WM material was significant, $F(1, 13) = 8.04$, $p = .014$, thus indicating the dual-task cost of WM in the colour-location condition (mean $K_r = .49$) was greater than that in the colour-shape condition (mean $K_r = .08$); other effects were not significant. Again, we did t-tests separately on each condition to examine whether the relative dual-task cost (K_r) in that condition was different from zero. The dual-task costs of WM in the colour-location condition at set size two and four were significantly above zero, $t(13) = 3.91$, $p < .01$, and $t(13) = 6.83$, $p < .01$, respectively, whereas the dual-task costs of WM in the colour-shape condition at set sizes two and four were not different from zero. Therefore, after the correction for the baseline performances it is safe to conclude that WM performance was impaired in the dual task condition only when the content of the WM was spatially specific.

As we expected, the dual-task interference between visual WM and MOT is specific to spatial WM tasks. Parallel to that of Fougnie and Marois (2006), we found that the performance of spatial WM is impaired by the concurrent MOT task. But we also found that the maintenance of nonspatial WM is not influenced by performing MOT (at least with a set size of 2). It has been shown that spatial WM and nonspatial WM are impaired to the same extent by random-number generation, which requires generation of a random sequence of numbers between 1 and 10 and is supposed to demand on general executive functions such as the inhibition of dominant responses and information updating (Klauer & Zhao, 2004). Therefore, the disproportional effect of MOT on spatial WM and nonspatial WM found in this experiment suggests that a primarily spatial resource might be involved in performing the MOT task, which is not consistent with the Visual Index theory. We discuss this issue more in the General Discussion.

Besides, the performance of MOT does not become worse when WM is occupied, nor does it decline as the memory load increases from two objects, a modest load, to four objects, a severe load. If objects in WM and objects in perception have one and the same limit, one would predict a competition between the objects being tracked and the objects being remembered. Yet the present results seem to indicate the dissociation between visual objects and objects held in WM.

The index seemed quite low (as low as about one object) in Experiment 1. In fact, according to the computation equation, for perfect performance, when = = 1, = –1. Thus, when the set size is 2, the maximum is 1; and when the set size is 4, the maximum is 3. Therefore the results of Experiment 1 showed that participants' performance were near perfect in the condition of set size 2; and lower but still acceptable in the condition of set size 4. According to Xu and Chun (2006), WM capacity is determined both by a fixed number of objects and by object complexity. Previous studies found can be as low as 1.6 or even 1.4.

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in the centred condition would be far less processed than that in the dispersed condition because locations of the stimuli in the centred condition were fixed, whereas those in the dispersed condition were randomly selected.

Twenty-eight paid participants, 19–25 years of age, were tested. All reported normal or corrected-to-normal vision and normal colour vision. None of them had participated in Experiment 1. Fourteen of them were randomly assigned to the centred condition and the other fourteen to the dispersed condition.

The MOT displays in Experiment 2 were identical to those in Experiment 1 except that the number of targets could be one, two, or four.

Each item in the WM tasks subtended 1.0°. The sample display was three coloured squares. To match the difficulty of our colour memory tasks with that of Fougnie and Marois (2006), we used 10 candidate colours. Seven of colour squares appeared at three randomly selected locations among six possible ones, which were 3.4° from the fixation cross and dispersed equally on an imaginary circle. The probe display was a single colour square at the centre of the screen.

Like Experiment 1, there were three kinds of tasks, MOT-only, WM-only, and WM-MOT.

[illegible]. The procedure was the same as that of Experiment 1 except that the number of targets could be one, two, or four.

[illegible]. The basic procedures were like those of Experiment 1 with the following excepti9.9621The8.7(-onl)16.9(y)8-8(-onl)16sicTWM-264 where l is the set size of colours,

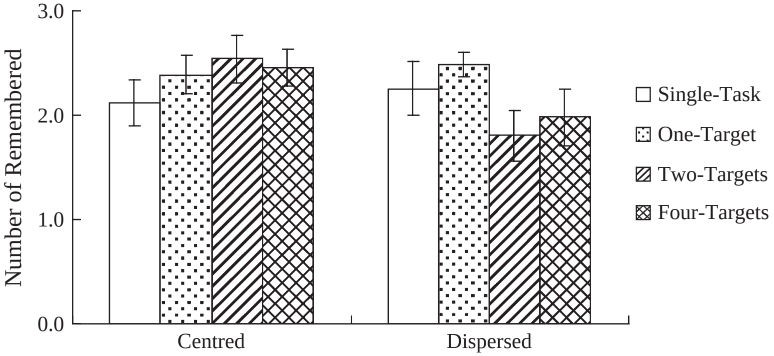

Figure 7. Mean number of colours remembered of Experiment 2, as a function of layout group (centred or dispersed) and MOT load (single-task, one target, two targets, or four targets). Error bars show standard errors.

4.70, $p = .01$. No main effects were significant. Simple effect analysis revealed that number of targets had no effect on the centred group, but had a significant effect on the dispersed group, $(2, 26) = 7.75$, $p < .01$. According to a post hoc comparison, for the dispersed group, tracking two or four targets impaired WM to a larger extent than tracking one target did.

To preclude the effect of baseline differences, we compared the baseline WM scores of the centred group (mean = 2.12) and the dispersed group (mean = 2.25) by a t-test and found no significant differences.

The results of Experiment 2 confirm our speculation that the spatial layout difference in WM sample displays is the cause of the inconsistency between our Experiment 1 and Experiment 6 of Fougnie and Marois (2006). The WM of the dispersed group but not that of the centred group is subject to MOT interference. Therefore, it is tenable to conclude that the maintenance of nonspatial WM is not influenced by performing MOT.

This difference between the two layout conditions may be an effect of automatic representation of spatial information, which is consistent with several recent studies (Hollingworth, 2007; Treisman & Zhang, 2006). It has long been known that task-irrelevant spatial information can be automatically represented, as shown by the compatibility effect of the spatial property of a stimulus and its response (Lu & Proctor, 1994), or by the effect of WM for shapes on the pattern of eye movements, in which where the shapes originally appeared makes a difference (Meegan & Honsberger, 2005). In the centred condition, the sample colours stay at the same locations in each trial, which may lead participants to neglect the spatial properties of them. In contrast, in the dispersed condition the locations of the sample colours vary with trials, which may be noticed and induce a representation of colours based on locations. When the memory of locations is disrupted by MOT, the representation of colours accompanied with locations is also impaired. In this way, only the retention of the dispersed condition but not that of the centred condition is subject to MOT. Another possible explanation is that the items in the dispersed condition cannot be so richly processed as those in the centred condition, for the attentional resolution drops rapidly with eccentricity (Intriligator & Cavanagh, 2001), or for the density of processing resources decreases as the size of the attentional field increases (Eriksen & St. James, 1986), and thus are more difficult to enter WM. A third possibility is that maintaining colours is more resource demanding in the dispersed condition than in the centred condition, and therefore the WM in the dispersed condition is more fragile in the face of interference. The latter two possibilities can be excluded by the fact that single-task memory performances of the two layout conditions are alike but far from perfect.

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In the present study, with a WM-MOT dual task paradigm, we found that spatial WM but not nonspatial WM is impaired by MOT and task-irrelevant spatial factors can determine whether WM is susceptible to interference by a concurrent MOT task. To be more specific, in Experiment 1, WM of colour-location conjunction but not of colour-shape conjunction was showed to be impaired by a concurrent MOT task; in Experiment 2, WM for coloured patches were demonstrated to be unaffected by MOT when their locations were fixed and constrained in a more compact layout. Furthermore, participants' performances of the MOT task seemed to be insensitive to WM load, no matter it is empty or full. These results imply that objects in WM and objects that are selected in MOT do not compete for the same

one of the targets the observer has to compare the cued objects with a selected object. Consequently making a response in an MOT task logically

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