Visual spatial attention and spatial working memory do not draw on shared capacity-limited core processes

Christina J. Howard[1], Rebekah Pole[1], Paulina Montgomery[1], Amanda Woodward[1], Duncan Guest[1],
Bradley Standen, Christopher Kent[2] and Emily M. Crowe[2, 3]

[1]Department of Psychology, Nottingham Trent University
50 Shakespeare Street, Nottingham, NG1 4FQ, United Kingdom

[2]School of Psychological Science, University of Bristol,
Priory Road, Bristol, BS8 1TU, United Kingdom

[3] Department of Human Movement Sciences, Vrije Universiteit Amsterdam,
De Boelelaan 1105, 1081 HV, Amsterdam, Netherlands

Abstract

The extent to which similar capacity limits in visual attention and visual working memory indicate a common shared underlying mechanism is currently still debated. In the spatial domain, the multiple object tracking (MOT) task has been used to assess the relationship between spatial attention and spatial working memory though existing results have been inconclusive. In three dual task experiments we examined the extent of interference between attention to spatial positions and memory for spatial positions. When the position monitoring task required keeping track of target identities through colour-location binding, we found a moderate detrimental effect of position monitoring on spatial working memory and an ambiguous interaction effect. However, when this task requirement was removed, load increases in neither task were detrimental to the other. The only very moderate interference effect that remained resided in an interaction between load types but was not consistent with shared capacity between tasks – rather it was consistent with content-related crosstalk between spatial representations. Contrary to propositions that spatial attention and spatial working memory may draw on a common shared set of core processes, these findings indicate that for a purely spatial task, perceptual attention and working memory appear to recruit separate core capacity-limited processes.

Introduction

Whether or not spatial working memory and spatial attention are truly dissociable processes has implications for the debate around the independence of attention and memory more generally, and beyond the specific context of spatial processing. Visual working memory has been described as the short term storage of visual information in order to be able to manipulate that information for the purposes of the task at hand (Baddeley & Hitch, 1974). It has been proposed as an interface between other processes such as perception, attention, short term and long term memory (Cowan, 2008). In these conceptualisations, attention and working memory are closely linked, and both working memory (Awh, Barton & Vogel, 2007) and visual attention (Alvarez & Franconeri, 2007) appear to be similarly highly capacity-limited. We might expect a close relationship since both are associated with activity in the fronto-parietal network (Awh, Smith & Jonides, 1995; Awh & Jonides, 1998; Corbetta, Kincade & Shulman, 2002; LaBar et al., 1999). It has been proposed that visual attention and working memory are closely related functions of the cognitive system (e.g. Gazzaley & Nobre, 2012; Oberauer, 2019) although the precise nature of this close relationship is still under investigation. Chun (2011) has argued that visual working memory and visual attention are so closely intertwined that visual memory can be considered as visual attention directed to internal representations. Others (e.g., Awh, Vogel & Oh, 2006) have suggested that visual attention acts both to select visual information at the perceptual stage of processing but also at post-perceptual stages such as the selection of objects or stimuli to be maintained in working memory. Memory rehearsal also appears to recruit visual attention: this is seen in neuroimaging evidence (Postle et al., 2004) and spatial rehearsal facilitates perceptual performance at to-be-remembered locations relative to irrelevant locations (Awh & Jonides, 2001). Others have shown that attention and working memory appear to share resources to some extent: Close et al. (2014) suggested resource sharing between spatially directed attention and the spatial memory processes recruited during spatial cueing In dual task interference paradigms, some studies report dual task interference between visual attention and working memory tasks under high loads (Feng, Pratt & Spence, 2012). However, others report no detrimental effect of an attentionally demanding search task on a working-memory loading colour change detection task (Hollingworth & Maxcey-Richard, 2013). To add to this somewhat mixed literature, Tas, Luck and Hollingworth (2016) have shown that overt but not covert attention interferes with a visual working memory task. Therefore, the circumstances under which visual attention and visual working memory appear to draw on common resources is by no means fully resolved either generally or with specific regard to spatial attention and spatial working memory in particular.

The current work addresses the extent to which visual spatial attention and visual spatial working memory interfere with each other using the multiple object tracking task (MOT; Pylyshyn & Storm, 1988). The multiple object tracking task requires participants attempt to keep track of targets as they move amongst distractors and was chosen here for several reasons. First, it can be used to engage spatial attention under varying dual-task conditions with different memory load demands and therefore to answer the currently unanswered question in the literature around the extent of interference between spatial attention and spatial memory processes. Second, because tracking tasks enable us to engage spatial attention as the primary aspect of the task, with or without any additional requirement to attend to or encode any non-spatial features of objects (such as colour). Third, it was also chosen because investigating the relationship between spatial attention and spatial working memory in the context of tracking will be informative regarding parallel and serial accounts of divided attention and tracking processes. Some accounts of MOT involve a serial processing element (d’Avossa et al., 2006) especially if any identity information must also be encoded about moving targets (Oksama & Hyönä, 2008). Tracking models containing a serial element suggest that target representations may be supported by a spatial memory component whilst the tracking mechanism is temporarily allocated elsewhere and away from recently attended targets. This is consistent with evidence that participants sometimes display perceptual lag, or the tendency to report slightly out-of-date positions of moving targets (Howard & Holcombe, 2008; Howard, Masom & Holcombe, 2011), as would be expected if target positions were refreshed to some extent serially in memory. However, these data are not conclusive regarding serial processing since they are also consistent with other accounts such as slowed parallel processing under high loads. It is also important to note that this would not mean that a memory component is necessary for tracking, only that it can be used under some circumstances, for example when load is high or as a consequence of specific strategies adopted by participants. Using sequential versus simultaneous presentations of tracking stimuli, some have argued against serial component to the tracking resource (Howe et al., 2010) which would therefore not imply a role for spatial working memory in tracking. However, it is not known whether the parameters of these experiments (e.g. duration or frequency of sequential motion periods) were set at a level at which a potential memory-supported tracking mechanism could operate. Therefore, the debate around serial and parallel contributions to the tracking mechanism is ongoing. Serial switching of attention between targets would rely on a memory buffer of recently attended targets so that attention can return near to the last stored position of a given target after visiting other targets and refreshing their representations in memory. Reducing this support from memory (for example, by placing it under load from another memory-related dual task) could decrease performance generally in terms of reduced accuracy for target position. In particular it should also exaggerate perceptual lags, since memory representations may not be updated fully on every visit from attention, leading to memory representations being even more ‘out of date’ than they would otherwise be. The role of memory in tracking is therefore informative as to the nature of the tracking process, with serial processes being more reliant on memory and so more sensitive to memory demands from other sources. This would be the case for models of tracking featuring discrete ‘pointers’ such as the FINST model (Pylyshyn & Storm, 1988) or for more recent accounts conceptualising the tracking resource as more flexibly distributed between targets (Alvarez & Franconeri, 2007).

Many MOT studies provide evidence about the relationship between spatial working memory and tracking, however this evidence is mixed. Flombaum, Scholl, and Pylyshyn (2008) used an MOT task in which targets and distractors occasionally passed behind occluders. They found that detection responses to the appearance of probe targets were actually superior when presented at the location of an occluded target than they were when presented at the location of visible targets. These authors attributed this finding to spatial attention being allocated to the locations of occluded targets. It is unclear whether this effect was wholly or partially underpinned by spatial memory resources, and if so, whether memory was recruited solely as a response to occlusion or whether it was involved in tracking even when no occlusion events occurred. Drew et al. (2011) showed that although MOT and working memory tasks produced similar patterns of EEG activity, there was unique additional activity associated with tracking. Carter et al. (2005) administered psilocybin, a serotonin agonist, to participants in an MOT task since its general effects on vigilance had been suggested (Hasler et al., 2004). They reported a reduction in MOT performance but no effect on a spatial working memory task. They suggested that psilocybin affected the inhibitory aspect of MOT required to suppress attention to distractors.

Dual task paradigms have also been used to examine the interference between tracking and spatial memory tasks. Postle, D’Esposito and Corkin (2005) showed that MOT disrupted a spatial N-back task. Perhaps surprisingly, the MOT task also disrupted an N-back based on memory for object identities with no explicit spatial task requirement. Since it has been suggested that spatial and visual (non-spatial) WM are dissociable functions of the brain (Carlesimo et al., 2001), this therefore questions the specifically spatial nature of any interference seen between MOT and the spatial N-back task. Allen et al. (2006) reported that spatial tapping as a spatial working memory task interferes with MOT but not as much as other tasks engaging visual-verbal working memory tasks. Both of these studies show either similar or greater interference between MOT and non-spatial working memory tasks as are seen between MOT and purely spatial working memory tasks, which calls into question how much of these interference effects between tracking and memory tasks is specifically spatial in nature.

Several authors have investigated the role of working memory during MOT by using various dual task paradigms that use either colour encoding or colour change detection as the memory-loading task. It is not clear to what extent these findings may generalise to tasks with purely spatial processing requirements (without the need to attend to or encode non-spatial information) for both the attention and working memory tasks. Makovski and Jiang (2009) showed that tracking was enhanced for displays with uniquely coloured objects. In these experiments, participants appeared to be encoding colours in order to differentiate targets from distractors and this placed a load on visual working memory. Although encoding colour information reduced tracking performance in some experiments, in some cases, it produced an overall tracking benefit via target-distractor differentiation, especially under conditions of greater crowding. This appears to indicate at least partially independent resources between tasks since this colour encoding appears to have taken place even under dual-task conditions with a highly attention-resource demanding version of the tracking task. Lapierre, Cropper and Howe (2017) demonstrated interference between tracking and working memory tasks using a colour-location binding task to recruit visual working memory. They noted that interference was variable between experiments and sensitive to sources of experimental noise such as individual differences and the order of report between tasks. Additionally, as they used a colour-location binding task to assess visual working memory, it is not clear whether the spatial memory component of the task contributed to interference effects seen. Other evidence from dual task paradigms suggests a dissociation between visual working memory and MOT resources. Souza and Oberauer (2017) compared interference from secondary visual and auditory attention tasks on two primary tasks: a visual working memory task and MOT. These authors reported a dissociation whereby the secondary visual attention task interfered with MOT but not the working memory task and the secondary auditory attention task interfered with the working memory task but not MOT. They concluded that MOT and visual working memory are dissociable, with MOT but not visual working memory depending on visual attention resources. However, their working memory task involved maintaining colour-location binding, so it is not clear whether similar results would have been found for a purely spatial working memory task.

Several studies suggest that interference between MOT and working memory tasks relies on the memory task necessitating spatial information processing. Fougnie and Marois (2006) showed that a colour-location binding visual working memory task could impair tracking, and that MOT impaired a visual working memory task (Fougnie & Marois, 2009) particularly when the memory task involved binding features together based on their shared locations. Zhang et al. (2010) used dual-task experiments with tracking performed alongside a range of working memory tasks. Tracking appeared to impair the working memory task depending on the extent to which the working memory task involved either explicit (binding colour-shapes to location) or implicit (location is task irrelevant but may still have been encoded) spatial processing.

Another approach used to explore the association between spatial working memory and tracking is through between-subject comparisons. Oksama and Hyönä (2004) showed an inter-individual correlation between tracking capacity and Corsi block tapping and Bettencourt, Michalka and Somers (2011) showed correlations between individuals' performance on MOT and visuospatial memory tasks. Similarly, Trick, Mutreja, and Hunt (2012) reported correlations between MOT performance and both spatial working memory and visuospatial working memory measures. Störmer et al. (2012) suggested that there are small but significant correlations between visual-spatial working memory capacity and MOT performance. O'Hearn, Hoffman, and Landau (2010) tested typical and atypically developing individuals and suggested a developmental dissociation between MOT and spatial working memory. Therefore, the literature using individual differences and between-subject variability is somewhat equivocal on the relationship between spatial memory and spatial attention.

The question of the relation between attention and memory has also been explored using visual search. Woodman and Luck (2004) showed bidirectional interference between search and a concurrent spatial working memory task. Some authors (Soto et al., 2005; Olivers, Meijer & Theeuwes, 2006; van Moorselaar, Theeuwes & Olivers, 2014) have identified reliable effects of memory processes on visual search tasks. These effects appear to be based on visual similarity of the non-spatial features of items in the memory and search arrays, often causing interference in the search task, or facilitation when the items in memory are visually similar to search targets. Conversely, Hollingworth and Maxcey-Richard (2013) found no effect of a search task inserted into the retention interval of a colour memory task. Visual search is a memory-based task insofar as each display item needs to be compared to the target item held in memory. Whilst bottom up saliency factors play a role, most models of visual search assume that some measure of the similarity between a target and distractors is used to guide search (e.g., Duncan & Humphreys, 1989; Guest & Lamberts, 2011; Wolfe, 2004). Although it is possible that “memory” could be instantiated by a set of feature weights that are defined prior to the task, it is probable that such weights are dynamically changed over the course of a search in order to aid search (e.g., Logan, 2002; Guest & Lamberts, 2011). A memory component is required whether search is serial or parallel. Data from visual search studies are informative regarding low level properties and processes underpinning attention, because the time course of a trial is relatively brief (typically search is completed under 2 seconds and often much faster). In such a fast task, low level properties of the attention system dominate processing. In comparison the MOT task is completed over a much longer timescale, and thus requires sustained attention. Moreover in MOT, participants know in advance which items they should attend to and do not search for them. The nature of distracting items in the display is also known, limiting uncertainty. There is only a memory component in tracking if it is completed by serially switching attention between target items, in which case memory is required to know the last position (and potentially also the trajectory) of target items. Thus, the question of overlap between memory and attention in MOT pertains to a theoretical question regarding the nature of the processes underpinning MOT. The same is not true of search, where the question is more about the extent to which memory is involved.

Table 1: *Summary of Previous Studies Examining the Relationship Between Visual Memory and Visual Attention.*

Publication	Methods	Results	Relevance to current study	Key points of differentiation from current study
Modified MOT tasks				
Howe et al. (2010)	Sequential versus simultaneously moving objects	Simultaneous condition no worse than sequential. Interpreted as evidence for parallel account, therefore spatial WM not implicated as part of tracking mechanism.	Indirectly assesses role of spatial WM in tracking through assessing parallel and serial accounts.	Does not directly assess possible shared resource between attention and spatial WM processes.
Drew et al. (2011)	Compared electrophysiological responses to various tasks. Expt 1: tracking contrasted with colour-location binding in VWM. Expts 1b and 3: tracking contrasted with spatial WM.	Similar electrophysiological (CDA) response and load-dependence for tracking and WM tasks. However, greater CDA amplitude for tracking than WM and specifically spatial WM.	Suggests some (but not total) overlap between tracking and spatial WM processes with some processing being unique to tracking.	Examines electrophysiological correlates of attention and spatial WM tasks. Does not directly assess whether the two tasks share the same cognitive resources.
Flombaum, Scholl & Pylyshyn (2008)	Introduced retention periods during tracking by means of occluding objects. Participants attempted to detect probes at various locations in the display.	Better performance at locations of occluded targets, suggesting representations of occluded targets in spatial WM.	Suggests that spatial WM can be used to support representations of tracking items, perhaps strategically.	Does not examine compulsory resource sharing between attention and spatial WM.
Carter et al. (2005)	Administered psilocybin to induce vigilance reduction.	Psilocybin reduced performance on MOT but not spatial WM.	Suggests possible dissociation between spatial WM and MOT tasks.	Does not directly assess whether the two tasks share the same cognitive resources.
Dual tasks without colour				
Postle, D’Esposito & Corkin (2005)	Spatial N-back and object N-back used to engage WM. Interference from MOT and a verbal-semantic task examined.	MOT disrupted the spatial N-back task. MOT also disrupted non-spatial N-back.	Suggests shared resources between attention and WM.	N-back tasks may have placed a heavy load on executive function e.g. comparison of memory items. Therefore unclear how these results would

				generalise to spatial WM task with fewer executive function demands.
Allen et al. (2006)	Interference on MOT measured from a number of secondary WM task measures.	Spatial WM task (spatial tapping) interfered with MOT. Non-spatial secondary WM tasks (verbal categorisation task) also caused interference.	MOT appears sensitive to WM tasks and generally to executive function loads.	Spatial tapping condition similar to current study but does not directly assess load-dependent capacity sharing between spatial attention and WM processes.
Fougnie & Marois (2006) Experiment 5	Administered purely spatial VWM task to assess interference with MOT.	Demonstrated interference between tasks.	Suggests shared resources between spatial attention and spatial VWM.	Similar to current study though precision of representations in attention and spatial WM not measured directly.
Dual tasks using colour				
Lapierre, Cropper & Howe (2017)	Administered MOT task and VWM tasks under dual task conditions.	Dual task interference shown. Also noted large contribution of response order.	Suggests shared resources between attention and VWM.	VWM task required non-spatial feature (colour) encoding. Therefore contribution to this interference from purely spatial aspects of memory processes not established.
Souza & Oberauer (2017)	MOT task vs VWM task (colour location binding) and secondary auditory or visual distractor task.	Visual distractor task impaired MOT performance most and conversely, auditory distractor task impaired VWM task most.	Suggests dissociable processes between MOT and VWM.	VWM task required non-spatial feature (colour) encoding. Therefore contribution to this interference from purely spatial aspects of VWM processes not established.
Fougnie & Marois (2006)	MOT and colour-location binding VWM task.	Interference between tasks.	Suggests shared resources between attention and VWM.	VWM task always required non-spatial feature (colour) encoding (though see Expt 5 listed above).
Fougnie & Marois (2009)	MOT and range of VWM tasks involving different features, feature conjunctions and memory items at distinct or central locations.	MOT impaired VWM especially when the VWM task involved binding features together based on their distinct locations.	Suggests shared resources between attention and VWM, especially with regard to encoding non-spatial features with spatial processing.	Relationship specifically between spatial attention and spatial memory not tested directly because memory (VWM) task always required encoding non-spatial features.
Zhang et al. (2010)	Administered MOT alongside various WM tasks that either involved explicit spatial processing, no spatial processing or implicit spatial processing.	Working memory tasks involving implicit and explicit spatial processing impaired by MOT.	Suggests shared resources between spatial WM and attention.	WM task always required non-spatial feature (colour and sometimes shape) encoding. Purely spatial aspects of interference between tasks not established.
Individual differences				
Bettencourt, Michalka & Somers (2011)	Administered MOT and VSTM (colour change detection) tasks.	Inter-individual correlation but only when the two tasks matched for number of distractors	Suggests common processes may underlie VSTM and MOT tasks.	Direct causal inferences not possible in this correlational design. Results consistent with some shared processes between tasks. These shared processes may include distractor filtering. Design does not allow conclusions on

				contribution of purely spatial encoding to this relationship.
Trick, Mutreja & Hunt (2012)	Administered MOT as well as Corsi blocks (spatial WM) task, Visual Patterns test (visuospatial WM), digit span and other non-spatial span measures.	Spatial and visuospatial WM accounted for the most variance in MOT.	Suggests common processes may underlie spatial and visuospatial WM and MOT tasks.	Direct causal inferences not possible in this correlational design.
Störmer et al. (2012)	Administered MOT and spatial updating WM task with younger and older adult sample.	Correlations between tasks for both age groups.	Suggests common processes may underlie spatial WM and MOT tasks.	Direct causal inferences not possible in this correlational design.
O'Hearn, Hoffman & Landau (2010)	Administered MOT and spatial WM with typically developing children and individuals with Williams Syndrome.	Individuals with Williams Syndrome particularly impaired at MOT compared to typically developing children.	Suggests dissociation between at least some aspects of MOT task and spatial WM.	Direct causal inferences not possible in this correlational design.
Oksama & Hyönä (2004) Experiment 1	Administered MOT and visuospatial WM task (Corsi-Block-Tapping-Test)	Correlation between MOT and visuospatial WM capacity.	Suggests common processes may underlie visuospatial WM and MOT.	Direct causal inferences not possible in this correlational design.
Visual search (key studies)				
Woodman & Luck (2004)	Dual task: visual search and spatial WM task.	Visual search slowed under dual task conditions. Spatial WM task accuracy decreased under dual task conditions.	Indicates close relationship between attention and spatial WM.	Attention task (search) requires use of top-down template for target identification. Unclear whether the same relationship with spatial WM would pertain if this were not required.
Soto et al. (2005)	Visual search performed whilst items were maintained in WM. Search-irrelevant items could be congruent or incongruent with the items in WM.	Content-related interactions shown between the two tasks. Attention appeared to be drawn to search-irrelevant items that matched the appearance (colour, shape) of the items held in WM.	Indicates close relationship between attention and WM.	Indicates content-related interference between attention and WM. Interference depends on similarity of non-spatial features (colour, shape) but does not address whether this result would pertain with interference based on spatial information. Does not directly assess capacity sharing between attention and WM processes.
Olivers, Meijer & Theeuwes (2006)	Used a search task in the retention interval of a feature based WM task.	Content-related interference shown between the two tasks. Interference arose through capture by search distractors that shared the colour or shape of items in WM.	Indicates close relationship between attention and WM.	Indicates content-related interference between attention and visual WM. Interference depends on similarity of non-spatial features (colour, shape) but does not address whether this result would pertain with interference based on spatial information. Does not directly assess capacity sharing between attention and WM processes.
Van Moorselaar, Theeuwes & Olivers (2014)	Used a search task in the interval of a change detection task to test interference between search and WM	For WM load of a single item, interference appeared in the search task. Interference arose	Indicates close relationship between attention and WM but only for single memory loads.	Indicates content-related interference between attention and visual WM. Interference depends

	processes. Measured attention capture in search task by items stored in visual WM for change detection task.	through capture by search distractors that shared the colour of items in WM.		on similarity of non-spatial features (colour) but does not address whether this result would pertain with interference based on only spatial information. Does not directly assess capacity sharing between attention and WM processes.
Hollingworth & Maxcey-Richard (2013)	Used a search task in the interval of a visual WM task (change detection) to test interference between search and WM processes.	Search had no effect on ability of attention to prioritise one item in WM array. Search efficiency was not reduced by prioritisation of one item in WM.	Consistent with independence of WM and attention processes.	Both WM and attention tasks always involved non-spatial feature encoding (colour, shape). Therefore unknown whether the same result would pertain for purely spatial attention or WM tasks.

In the current study we used a dual task paradigm to assess the extent to which a spatial memory task and a spatial attention task (MOT) interfere with one another. Our design was chosen to enable direct assessment of the extent to which the two tasks interfere with one another with spatial encoding as the core task in both cases and in a design that permits a version involving no non-spatial feature encoding and highly similar stimuli for both tasks. Based on the previous literature (see Table 1 for a summary), we hypothesised that substantial interference would be evident between the tasks generally and may arise in dual task costs on spatial attention or spatial working memory performance or on both tasks. We used a purely spatial working memory task, where participants were required to encode and later report the positions of a variable number of memory targets. To engage spatial attention, we asked participants to continuously monitor and subsequently report the changing positions of a variable number of tracking targets. We chose this spatial attention task in preference to visual search since we wanted the spatial characteristics of targets to be the primary task demand (rather than target identity on the basis of non-spatial features) and also to allow us to use a version of the task in which only spatial information (i.e. no non-spatial features) is relevant (Experiment 3). In both tasks, we measured the precision of these position representations by prompting participants to report the position (the final position in the tracking task) of one queried target from one or other task. In Experiments 1 (spatially overlapping memory and attention displays) and 2 (spatially separated memory and tracking displays), in order to make this position monitoring task more similar to traditional MOT tasks, we had targets move amongst distractors. The identity of the queried target was then queried by means of its colour. In Experiment 3, we removed any involvement of feature encoding such as colour-location binding and employed a task requiring attention and memory solely for spatial positions of targets. In this way, any detrimental effects of the memory task on tracking performance can be attributed solely to spatial memory. As well as examining position accuracy we also assessed effects of the dual task on perceptual lags in the position monitoring task. If the position tracking mechanism includes a serial attentional process supported by memory representations of recent past positions of targets, then placing the memory store under additional load may reduce the quality of updating of position representations in memory. We therefore hypothesised that increasing memory load during the position tracking task would exaggerate perceptual lags.

Experiment 1

Method

Design

Participants took part in a dual task experiment involving a spatial memory task and a position tracking task (see Figure 1). Participants were first presented with a memory array comprising eight stimuli, one presented in each octant of a square. Participants were asked to encode either one or three memory targets. They were then presented with an array of eight coloured (red, yellow, blue, green) tracking stimuli, three of which were designated as targets with no two targets sharing the same colour. After the motion period of the tracking display, participants reported the final position of one queried tracking target (queried via a coloured probe) and then one memory target (queried via probing an octant). Participants were not instructed to use any prioritisation of one task over another and were told that attempting to perform both tasks to the best of their ability was important. Participants were given a series of practice trials (up to around 10 or until the participant felt familiar with the procedure). Participants took part in four blocks of 60 trials, and the two memory load conditions were intermixed within blocks.

Participants

Twenty participants, four of whom were male took part in this experiment with a mean age of 26.0 years. All had normal or corrected-to-normal vision, none reported problems with colour blindness or reported a history of neurological conditions.

Stimuli and procedure

A computer programme written in Python using the VisionEgg library (Straw, 2008; www.visionegg.org) displayed stimuli on a CRT screen at 1,024 x 768 pixel resolution refreshing at 85 Hz. Observers viewed the display at a distance of 0.4 m in a dimly lit room.

On every trial, participants were presented with a grid superimposed on a mid-grey (18.04 cd/m^2) background and with eight triangular regions surrounded around a central fixation point (see Figure 1). The triangular regions together formed an overall square shaped area measuring 21.6 x 21.6 degrees. One black (2.02 cd/m^2) disc (2.4 degrees in diameter) was presented at a randomly selected position within each triangular region (octant). On every trial, either one or three (selected randomly and with equal probability) of these targets were selected to be targets for encoding and this was indicated to the participant by means of the target(s) flashing black-white for 3,000 ms.

After this, the memory array disappeared and was replaced with eight coloured discs (two yellow, two red, two blue and two green, 2.88 degrees in diameter) each of whose positions was selected randomly and independently on every trial with the constraint that no two discs could overlap. On every trial, three of these tracking discs were selected at random to be tracking targets. In order to be able to uniquely probe the position representation of one of the targets at the end of each trial by means of its colour, we applied the constraint that no two targets could be the same colour as one another. We used two objects in each colour so that each target was always potentially confusable with its colour-matched distractor, thus encouraging participants to attempt to keep track of which objects were targets amongst the distractors during the trial. The targets were indicated to participants by means of flashing between black and their specific colour for 3,000 ms.

After the tracking target indication period, all discs underwent a period of smooth and random motion for 2,400-3,600 ms using the following motion algorithm: speeds and directions of motion were determined randomly and independently for each disc. For all discs, horizontal and vertical components of motion were set randomly between 4 deg/s and 44 deg/s producing a means speed of

24 deg/s. Discs changed direction of motion if they collided with one another or with the edge of the outer square tracking boundary according to the law of perfect elastic collisions.

After this period, all discs disappeared and the participant was presented with the tracking report prompt. One disc appeared at the centre of the display with a colour matching one of the targets. Participants moved this probe disc using the mouse to the final perceived position of the queried target and used a mouse click to enter this response. Participants were immediately given feedback in the form of the queried tracking disc in its final position. After the participant pressed the space bar, they were then immediately prompted to report the remembered position of one memory target (in the case of trials with a memory load of three, one of the memory targets was randomly selected to be queried) by means of a white bar whose location was at the outer edge of the octant that had contained that memory target. As soon as the participant started to move the mouse, a black disc (identical in appearance to the memory targets) appeared, which they moved to the remembered position of the queried memory target and clicked to make their response. Participants were then immediately given feedback in the form of the queried memory target in its original position. Participants then pressed the space bar to continue to the next trial.

Figure 1 about here

Figure 1: Representative trial timeline: in this trial, the participant is asked to encode the positions of three memory targets before attempting to track the three tracking targets. One disc is presented in each triangular area (octant) for the memory array. For the tracking array, all eight discs appear and subsequently move around anywhere within the large square region. On this trial, the yellow tracking target is queried.

Results and discussion

On every trial, we calculated the mean error magnitude, which is the spatial distance between the correct position of the queried target (in the case of tracking targets, this is the final position before it disappeared) and the reported position, in degrees of visual angle (see Figure 2).

We also used a Bayesian approach to our analysis, using the default priors in JASP (JASP Team, 2018). We report Bayes Factors in favour of the experimental hypothesis (BF_{10}) with the criteria of $BF_{10} > 3$ as evidence for the experimental hypothesis, and $BF_{10} < 1/3$ as evidence for the null, and $1/3<BF_{10}<3$ as ambiguous evidence. For each analysis (Bayesian repeated measures t-test and ANOVA) we also conducted a robustness check on the default priors used, we found no evidence that the conclusions we report are dependent on the particular priors used, except where noted.

For the tracking task, there was no difference between errors in the low (M=3.66 deg, SD = 1.65 deg) and high (M=3.51 deg, SD = 1.92 deg) memory load conditions ($t(19) = 0.62$, $p = .54$, $BF_{10} = 0.28$). The magnitude of these position report errors depends in part on the size of the tracking display, since the upper end of the range of potential errors is determined by the largest possible distances between correct and reported final positions. Therefore, it is difficult to compare the magnitude of these errors with those previously reported in similar tasks, but these are consistent with the range of mean error magnitudes typically reported as ~0.5-3.5 degrees (Howard, Arnold & Belmonte, 2017; Howard & Holcombe, 2008; Howard, Masom & Holcombe, 2011; Howard, Rollings & Hardie, 2017). For the memory task, errors were significantly greater in the high (M=2.95 deg, SD = .93 deg) than the low (M=1.73 deg, SD = .95 deg) memory load conditions ($t(19) = 8.79$, $p < 0.01$, $BF_{10} = 3.45 \times 10^5$). Therefore, whilst memory load directly affected the representation of spatial locations in the memory task, this memory load manipulation did not affect performance in attending to the changing positions of tracking targets. These results do not suggest a shared resource responsible for the two processes of spatial attention and spatial working memory.

Figure 2 about here

Figure 2: performance in the memory and tracking tasks under conditions of high and low memory load

For the tracking task, we also calculated perceptual lags (see Howard & Holcombe, 2008; Howard, Masom & Holcombe, 2011) by comparing position reports with near past and extrapolated near future positions of the queried tracking target (See Figure 3). To calculate perceptual lags on each trial, a series of distances are calculated between the participant's report of the final position of the queried target and the positions it had occupied in the final moments leading up to its disappearance at the end of the trial. In addition, a series of distances are calculated between the reported final position and the positions the queried target would have occupied had it continued moving in its final trajectory after the moment of its disappearance. Just as the mean error magnitude indicates the mean distance between the reported position and the veridical final position, perceptual lag analyses compare the reported position with a range of increasingly greater time differences (in the past or future) from the moment of disappearance (indicated at time zero and by the vertical line in Figure 3). For each participant we calculated these curves averaged over all the trials in each condition separately, producing one curve for each participant in each condition. Note that the perceptual lag figures depict the average of these individual curves, produced by averaging the points on the curve at each time point. The statistics reported below including mean lag times identified, represent the mean of the individual lag times (minima) identified for each participant in each condition. The mean of the individual minima and the minimum of the mean curves need not be identical values. The time at which these possible positions best resemble the reported position is found by localising the point on the curves that minimises these mean distances and this is the mean perceptual lag in this condition for this participant. The perceptual lag can be negative if participants' reports best resemble past positions and positive if reports best resemble extrapolated near future positions. For the low load condition, the mean lag was -50 ms (SD = 110 ms), for the high load condition the mean lag was -25 ms (SD = 25 ms) and these lags were not significantly different from one another ($t(19) = .73$, $p = .48$, $BF_{10} = 0.29$). These results do not suggest involvement of spatial working memory in the processes giving rise to perceptual lags in the tracking task, since manipulating the availability of memory resources had no effect on lags.

Figure 3 about here

Figure 3: mean perceptual lag curves for the tracking task under high and low memory load conditions

Experiment 2

In Experiment 1, memory and tracking arrays were presented in the same spatial region of the screen. The fact that both tasks involved processing stimuli in the same spatial region may have increased participants' ability to perform both tasks, since there was no requirement to divide processing over more than one broad spatial area. However, because the two task domains were fully spatially overlapping, another possibility is that there may be some spatial competition specifically due to the tasks sharing the same space. In Experiment 2 to investigate possible facilitatory or detrimental effects of the tasks sharing the same screen areas, we spatially separated the memory and tracking arrays. Memory arrays were presented solely in the upper half of the display and tracking arrays solely in the lower half of the display. We also used an additional tracking load condition such that for both the memory and tracking tasks, there could either be one or three targets on any given trial. Experiment 2 was identical to Experiment 1 but with the following differences. In Experiment 2, participants took part in two blocks of 60 trials with conditions intermixed within blocks and with equal number of trails in each of the four (2 memory loads x 2 tracking loads) conditions.

In Experiment 2, in order to accommodate the spatial separation between memory and tracking arrays, four rectangular areas of equal size were displayed in the upper area of the screen, one in which each disc would appear in the memory task (see Figure 4). As in Experiment 1, one of these areas was queried after the tracking report had been made by means of a white bar. In this experiment, these appeared at the upper edge of the areas. For the tracking task, discs only ever appeared in the lower half of the square area and were constrained within this lower half throughout the tracking period.

Method

Participants

Twenty participants, five of whom were male took part in this experiment with a mean age of 23.2 years. All had normal or corrected-to-normal vision, none reported problems with colour blindness or reported a history of neurological conditions.

Figure 4 about here

Figure 4: Example trial timeline for Experiment 2. On this trial, there are three memory targets and three tracking targets. The blue tracking target is queried, the participant then clicks on the final perceived position of the blue tracking target and is immediately presented with feedback in the form of the queried (blue) target in its veridical final position. After this, the leftmost of the three memory targets is queried, after which the participant makes their memory response and receives feedback.

Results and discussion

We calculated error magnitudes as for Experiment 1 (see Figure 5) and then performed a 2 (tracking load) x 2 (memory load) ANOVA for both (memory and tracking) tasks. For the tracking task as expected, there was an effect of tracking load ($F(1,19) = 88.26$, $p<0.01$, partial $\eta^2 = .823$, $BF_{10} = 4.99x10^{13}$) such that tracking more targets was associated with greater error magnitudes. There was no such effect of the memory load on tracking performance ($F(1,19) = .322$, $p=.577$, partial $\eta^2 = .017$, $BF_{10} = 0.31$) and no significant interaction ($F(1,19) = .891$, $p=.357$, partial $\eta^2 = 0.045$, $BF_{10} = 0.37$) though the Bayesian result for this interaction was classed as ambiguous (although as the width of the prior distribution was increased, this tended to evidence for the null). Inspecting Figure 5, the locus of this ambiguous interaction appears to be the difference between performance for a single tracking target between remembering a single item and remembering three items with performance actually being slightly better in the latter condition. The direction of this ambiguous interaction effect is not therefore consistent with dual task interference between tasks.

For performance in the memory task, there was an effect of tracking load ($F(1,19) = 12.991$, $p<.01$, partial $\eta^2 = .406$, $BF_{10} = 1.12$) although the Bayesian analysis suggested this effect is ambiguous. As expected, there was an effect of memory load ($F(1,19) = 167.88$, $p<0.01$, partial $\eta^2 = .898$, $BF_{10} = 8.72x10^{13}$) but no interaction ($F(1,19) = 0.148$, $p=.705$, partial $\eta^2 = .008$, $BF_{10} = 0.32$).

As for Experiment 1, spatial memory load affected the precision with which memory targets' locations were reported, and analogously, spatial attention load affected the precision of position reports for the tracking task. Tracking performance was unaffected by memory load as seen for Experiment 1. However, in this Experiment we are also able to assess the effect of tracking load on memory performance, and these data show a detrimental effect of tracking load on memory performance, with poorer quality memory reports in the high than low tracking load condition. However, the Bayesian analysis indicates that this effect is only ambiguous regarding rejection of the null hypothesis. The somewhat ambiguous effect of tracking load on memory performance is consistent with previous findings that memory for positions and position tracking may draw on some similar (although not necessarily completely overlapping) resources (Drew et al., 2011) and in particular that tracking tasks can disrupt performance in spatial memory tasks (Postle, D'Esposito & Corkin, 2005). However, in terms of the lack of effect of the memory load on tracking performance, these results contrast with others who report that tracking was affected adversely by memory tasks with an explicitly spatial component (Fougnie & Marois, 2006). These data therefore do not show clear evidence for dual task interference, and suggest, at most, mixed and minimal results regarding interference between the spatial attention and spatial memory tasks. We therefore investigate possible interference further in Experiment 3.

Figure 5 about here

Figure 5: performance for the tracking (top) and memory (bottom) tasks under high and low loads for tracking and memory tasks.

As for Experiment 1, we calculated perceptual lags for the tracking task. For tracking one target under memory load of one, lags were 20 ms (SD = 25 ms) (20 ms extrapolation). For tracking one target under memory load of three, lags were 10 ms (SD = 40 ms) (10 ms extrapolation). For tracking three targets under memory load of one, lags were -125 ms (SD = 190 ms) and for tracking three targets under memory load of three, lags were -115 ms (SD = 120 ms). We performed a 2 (tracking load) x 2 (memory load) ANOVA on these lags. There was an effect of tracking load ($F(1,19) = 26.64$, $p<.01$, partial $\eta^2 = .584$, $BF_{10} = 1.11x10^5$) such that tracking more targets was associated with greater lag magnitudes. There was no such effect of the memory load on lags ($F(1,19) < .001$, $p=0.989$, partial $\eta^2 < .001$, $BF_{10} = 0.23$) nor interaction ($F(1,19) = .235$, $p=.633$, partial $\eta^2= 0.012$, $BF_{10} = 0.33$ (0.330 to 3 d.p.).

Therefore, despite the presence of some mixed evidence for dual task interference in terms of the precision of memory reports and interactive effect on tracking performance (but no interactive effect on memory performance), there is no main effect of memory load on tracking performance or on perceptual lags in the tracking task. We do observe an effect of tracking load on perceptual lags, consistent with previous work (Howard & Holcombe, 2008; Howard, Masom & Holcombe, 2011). For a tracking load of one target, perceptual lags were negative i.e. position reports were slightly extrapolated. In previous work, slight extrapolation of this type has been observed under conditions of very low load and particularly when participants are attending to the motion of targets (Howard, Rollings & Hardie, 2017).

We also examined the extent to which the overall pattern of data matched what we would expect if attention and memory were being supported by an identical pool of processing resources. To do this, we performed two comparisons. First, we looked at the mean magnitude of the effects on tracking performance of increased tracking load versus increased memory load. Secondly, we looked at the mean magnitude of the effects on memory performance of increased tracking load versus memory load. If attention and memory were drawing on a single shared pool of resources, then both load types should have similar effects on performance for both the tracking and the memory task performance. In clear contrast to this, the effect of tracking load was more severe for tracking performance than the effect of memory load ($t(19) = 8.02$, $p < .001$, $BF_{10} = 95{,}244$). Similarly, the effect of memory load on memory performance was greater than the effect of tracking load ($t(19) = 6.85$, $p < .001$, $BF_{10} = 11{,}975$).

Figure 6 about here

Figure 6: mean perceptual lags under each condition for Experiment 2

Experiment 3

In Experiments 1 and 2 we used colour prompts at the end of the trial in order to query position representations. Since it is known that feature encoding is a resource demanding cognitive process (Luck & Vogel, 1997) and this is also the case during tracking (Saiki, 2003), we designed a further experiment in which no feature-based information was relevant at any time. Experiment 3 was therefore designed to remove any possible influence of the need to encode different colours. In addition, we also sought to reduce prioritisation of either task. In all of the experiments presented here, the tracking display is presented during the retention interval of the memory task. In Experiments 1 and 2, the tracking response was prompted prior to the memory response on every trial, to avoid introducing a retention interval to the tracking task. In Experiment 3, we sought to reduce any implicit prioritisation of the tracking task that may have arisen due to it being the first task responded to on each trial. Instead, we introduced a single report procedure whereby only one task was reported on every trial. On each trial, there was a 50% probability of either the memory or the tracking task being prompted at the response stage, and this response was prompted immediately after the presentation of the tracking display. Experiment 3 was identical to Experiment 2 with the following differences.

Method

At all times during Experiment 3, eight rectangular regions were drawn (see Figure 7), four in the upper portion of the display for the memory task (as in Experiment 2) and four in the lower portion of the display for the tracking task. During the tracking target identification phase, one black disc which was identical in appearance to the discs used for the memory task was presented in each of the lower areas at a randomly determined position, with either one or three of these flashing to indicate the target(s). During the tracking phase, each of these tracking discs moved around according to the previously described algorithm, constrained within its own tracking area. At the end of each trial, one target drawn from the total set of memory and tracking targets combined was queried by means of a white bar either at the upper edge (for the memory targets) or lower edge (for the tracking targets) of its area, and participants used a black test disc to make their report.

Participants

Twenty participants, eight of whom were male took part in this experiment with a mean age of 24.6 years. All had normal or corrected-to-normal vision, none reported problems with colour blindness or reported a history of neurological conditions.

Figure 7 about here

Figure 7: typical trial timeline in Experiment 3.

Results and discussion

We calculated error magnitudes and performed a 2x2 ANOVA for each task as for Experiment 2 (see Figure 8). For the tracking task, there was an effect of tracking load ($F(1,19) = 65.692$, $p < .01$, partial $\eta^2 = .776$, $BF_{10} = 4.66x10^7$) such that tracking more targets was associated with greater error magnitudes, but there was no such effect of the memory load on tracking performance ($F(1,19) = .513$, $p = .483$, partial $\eta^2 = .026$, $BF_{10} = 0.26$). There was however a significant interaction ($F(1,19) = 4.766$, $p = .042$, partial $\eta^2 = .201$, $BF_{10} = 0.82$), with memory load acting to decrease performance to a greater extent for tracking one target than for tracking three, although in the Bayesian analysis this was ambiguous. Traditionally interaction effects between dual tasks might be expected to indicate more severe effects at higher loads which is the opposite direction of interaction to the ambiguous interaction seen here.

For performance in the memory task, there was no effect of tracking load ($F(1,19) = 2.077$, $p = .166$, partial $\eta^2= .099$, $BF_{10} = 0.30$) but as expected there was an effect of memory load ($F(1,19) = 57.143$, $p < .01$, partial $\eta^2= .75$, $BF_{10} = 9.99x10^9$). There was no interaction between the effects of the two load types ($F(1,19)$ .015, $p = .904$, partial $\eta^2 = .001$, $BF_{10} = 0.29$). Overall then, neither dual task effect was apparent in the main effects i.e. tracking load did not directly affect memory performance, and memory load did not directly affect tracking performance. Unlike Experiment 2, there was no evidence for higher tracking loads being associated with poorer quality position reports in the memory task. The only interference effect in the data resided in the frequentist statistical analysis for the interaction between memory and tracking load effects for the precision of position reports in the tracking task. Similar to the results of Experiment 2, these findings contrast with previous work that has demonstrated adverse effects on tracking performance by disruptive memory tasks that involve spatial memory aspects (Fougnie & Marois, 2006). However, unlike Experiment 2, these results are not consistent with previous findings of disruptive effects of tracking on spatial memory tasks (Postle, D’Esposito & Corkin, 2005).

Figure 8 about here

Figure 8: performance in Experiment 3 for both tasks under high and low loads for tracking and memory tasks.

As for Experiments 1 and 2, we calculated perceptual lags for the tracking task. For tracking one target under memory load of one, lags were 10 ms (SD = 70 ms) (10 ms extrapolation). For tracking one target under memory load of three, lags were 15 ms (SD = 50 ms) (15 ms extrapolation). For tracking three targets under memory load of one, lags were -160 ms (SD = 260 ms) and for tracking three targets under memory load of three, lags were -50 ms (SD = 125 ms). We performed a 2 (tracking load) x 2 (memory load) ANOVA on these lags. There was an effect of tracking load ($F(1,19) = 12.352$, $p < .01$, partial $\eta^2 = .394$, $BF_{10} = 68.56$) such that tracking more targets was associated with greater lag magnitudes. There was no such significant effect of the memory load on lags ($F(1,19) = 3.122$, $p = .093$, partial $\eta^2 = .141$, $BF_{10} = 0.72$) nor interaction ($F(1,19) = 2.964$,

p=.101, partial η^2= .135, BF_{10} = 0.99) though the Bayesian analysis was ambiguous regarding the effect of memory load on lags and the interactive effect of both load types on lag magnitudes. However, the direction of these ambiguous effects is not what was predicted for the effect of spatial memory load on perceptual lags. For tracking three targets increasing memory load actually served to minimise perceptual lags instead of exaggerating them. Similar to what was seen in Experiment 2, and as expected, we see an effect of tracking load on lags, with more lagging responses seen for higher loads and slight extrapolation for lower loads, consistent with previous findings. Therefore, although these data appear to be somewhat inconclusive regarding the effect of memory load on lags we can conclude that there was no evidence for exaggerated lags under higher memory loads.

Figure 9 about here

Figure 9: mean perceptual lags under the different conditions for Experiment 3.

As we did for Experiment 2, we examined the extent to which the overall pattern of data matched what we would expect if attention and memory were being supported by an identical pool of processing resources. The effect of tracking load was more severe for tracking performance than the effect of memory load ($t(19) = 5.99$, $p < .001$, $BF_{10} = 2,370$). Similarly, the effect of memory load on memory performance was greater than the effect of tracking load ($t(19) = 5.23$, $p < .001$, $BF_{10} = 537$).

Discussion

We find that in the dual tasks presented here, spatial working memory tasks and spatial attention tasks can under some circumstances be associated with detrimental effects on one another’s performance. However, these detrimental effects appear to be minimal, mixed and dependent on specific parameters of the task, such that they can be almost entirely eliminated. In Experiments 2 and 3 we were able to directly compare the magnitude of effects within and between the two load types, with clear and consistent evidence that load increases within load type (i.e. the effect of tracking load on tracking performance and the effect of memory load on memory performance) were much more severe than the effects of load increases between load types (i.e. the effect of memory load on tracking performance and the effect of tracking load on memory performance). This is not consistent with spatial working memory and spatial attention processes drawing on a single resource. Instead, these highly moderate and mixed interference effects are much more consistent with other sources of interaction between these two processes, such as content-related crosstalk due to the similarity of information being processed by both: namely, spatial locations.

In Experiment1 there were no interference effects seen. In Experiment 2, there was no direct effect of spatial memory load on tracking performance. There was mixed evidence for an effect of tracking load on memory performance. Any direct interference caused by the tracking load on the memory task in Experiment 2 was absent in Experiment 3 when other task requirements were absent, such as the requirement to perform colour-location binding (to keep targets distinct from distractors) and the requirement to make the tracking response before the memory response. In Experiment 3, once these demands were eliminated from the task, the only interference effect that remained significant was in the frequentist analysis of the interaction between tracking load and memory load for the tracking task though this was not in the direction predicted by general dual-task load effects. In this experiment, there was no overall effect of memory load on tracking performance nor overall effect of tracking on memory performance. In terms of perceptual lags there was no effect of memory load in Experiments 1 or 2 and only ambiguous evidence in Experiment 3, though the direction of these ambiguous effects was not in the direction predicted by accounts of perceptual lags being due to involvement of spatial memory representations.

Taken together, the findings from these three experiments show that tracking load may impact memory performance to some extent in some conditions as in Experiment 2. Memory load does not appear to influence tracking performance directly, though there may be some moderate interactive effects. We also find no clear evidence for an effect of memory load on the magnitude of perceptual lags, which might be expected if location updating was supported by memory representations for recent past positions. Given that interference between spatial memory and position monitoring tasks appears to be only moderate in magnitude, often only shows up in mixed or ambiguous effects or in interactions between load effects, we propose that the core processes underlying the two tasks are distinct. Taken together, our findings are consistent with neuroimaging work suggesting dissociable brain areas involved in attentional tracking and working memory updating (Jahn et al., 2012) and dissociations in developmental trajectories for tracking and spatial working memory (O'Hearn, Hoffman & Landau, 2010).

Drew et al. (2011) used a range of tracking and visual working memory tasks to demonstrate some processing that was similar for the two tasks, and some processing that was specific to tracking. Both tasks elicited a similar electrophysiological response in terms of contralateral delay activity (CDA) that was dependent on set size, but an additional source of activity was associated with tracking. In some of these experiments, the visual working memory task involved colour-location binding and in those tasks it is possible that some of the observed differences between tasks were due to the non-spatial (i.e. colour related) aspects of the working memory task. However, in their Experiment 3, this aspect was removed from the task and working memory activity was evaluated by examining processing during stationary periods of a tracking display. In this experiment, the working memory and tracking requirements were both purely spatial in nature and the same findings held: the two tasks appeared to produce similar responses, but tracking elicited additional activity compared to simply maintaining targets' identity in terms of their spatial position in working memory. These results are partially similar to ours, since their conclusion was that spatial attention and spatial memory rely on some shared resources and some that were unique to the tracking task. Relatedly, Lapierre, Cropper, and Howe (2017) identified some mutual interference between tracking and working memory tasks, but since their working memory task involved colour encoding, it is not clear how much of this interference would have been seen had the working memory task been purely spatial in nature.

As shown in previous work (Howard & Holcombe, 2008; Howard, Masom, & Holcombe, 2011), the precision of position reports declines sharply with additions to attentional load even going from monitoring one target to monitoring more than one, consistent with the Flexible Resource account of attention used in tracking (Alvarez & Franconeri, 2007). If spatial memory load was subserved by the same resources as position monitoring, then we should expect a dramatic reduction in performance on the tracking task going from memory loads of one to three memory targets, since this would represent an increase from two to four total target objects (be they memory or tracking targets). Instead, the magnitude of tracking performance reduction with additions to memory load here is minimal in Experiments 2 and 3 and absent in Experiment 1. This suggests that position tracking does not draw on the same core resources as spatial memory. It is important to note however that this does not rule out the use of spatial memory to support tracking performance under some circumstances, such as during occlusion events (e.g. Flombaum, Scholl & Pylyshyn, 2008) or at high loads that may exceed the capacity of the tracking mechanism. Under very high loads above tracking capacity, it is likely the case that attention moves briefly away from some targets, leaving a memory representation of the last perceived position until attention returns again to refresh the currently represented position. Using direct measures of the precision of position representations, we are able to assess the extent of any shared processes at relatively small set sizes, where performance is much less likely to be contaminated by the use of such strategies that participants may adopt when their resources are taxed more heavily by the demands of the task.

The relative independence of spatial attention from spatial working memory resources we report here has implications for the perceptual lags previously reported for position tracking of this type (Howard & Holcombe, 2008; Howard, Masom, & Holcombe, 2011; Howard, Rollings, & Hardie, 2017). Perceptual lags where participants tend to report slightly out-of-date positions, rather than the last seen positions before the target display offset are often demonstrated in position monitoring tasks of this type, particularly under higher tracking loads. One possible explanation for perceptual lags has been that attention to changing positions draws wholly or in part on similar processes to those traditionally thought of as spatial memory processes. As discussed by Howard and Holcombe (2008), the time in the display that best matches participants' reports may well reflect the sum of several processes, each contributing to the overall balance of lagging and extrapolatory processes. For example, compensation may occur to account for neural delay, and motion processing may allow some extrapolatory component to position perception, particularly when attention to motion is encouraged (Howard, Rollings, & Hardie, 2017). However, other processes such as temporal integration of visual signals may cause perception to tend towards recent past positions of the target stimulus. Another key process which could potentially contribute to these lagging perceptual reports is the involvement of spatial memory representations from the very recent past. If this were the case, then we might expect a serial element to processing, whereby positions are serially refreshed in spatial working memory by attention, such as proposed by some (d'Avossa et al., 2006). However, the findings we present in Experiments 1 and 2 do not support this latter proposition, since placing load on the spatial memory resource did not exaggerate these perceptual lags. In Experiment 3, although the findings were less clear, the direction of any ambiguous effects of memory load on lag magnitudes were not consistent with this prediction.

Although we have stressed the importance of showing no clear consistent interference between spatial working memory, it is notable that we did find some evidence of this, albeit mixed and of moderate magnitude where it does show up in the data. This suggests that this paradigm is sensitive to capturing any such interference effects. Moreover, it helps explicate the conditions under which such interference may occur. In Experiment 2, colour-location binding was task-relevant, meaning that

that there were non-spatial as well as spatial aspects to the tracking task. Our results were somewhat consistent with the findings of Postle, D'Esposito & Corkin, (2005) and Allen et al. (2006), both of whom reported that tracking and non-spatial memory tasks interfered with one another at least to the same extent if not more than the interference seen between tracking and memory tasks with a spatial component. Our findings in Experiment 2 are also somewhat consistent with previous findings that tracking and colour-location binding in memory draw on common resources (Fougnie & Marois, 2006; Fougnie & Marois, 2009; Zhang et al., 2010). There are at least two reasons why the need to maintain and bind featural information with tracked objects may cause greater interference between tracking and memory tasks. In some cases, the informational complexity of object representations appears to affect the capacity of visual short term memory (Alvarez & Cavanagh, 2004) and therefore tracking more visually complex objects may demand a relatively large degree of memory resources in and of itself. There are likely additional demands arising from the need to keep bound representations of attended objects distinct from distractor objects that share features with targets (e.g. Lo, Howard, & Holcombe, 2012) such as attending to one green object and ignoring another. Other factors caused by the binding operation itself over and above the requirements from to-be-bound information (e.g. Luck & Hillyard, 1995) may also come into play here. Another potential explanation for the somewhat detrimental effect of tracking load on memory performance in Experiment 2 but not Experiment 3 could have been that the response method encouraged prioritisation of the tracking task over the memory task. In Experiments 1 and 2, the tracking task was always queried immediately after the offset of the tracking display and before the memory response was prompted. This prioritisation of the tracking task in terms of its primary position in the order of reports could have biased resources systematically towards tracking, and such order of reports have indeed been previously noted for memory and tracking tasks (Lapierre, Cropper, & Howe, 2017). It is possible that this led to the apparently unidirectional negative (although somewhat ambiguous) effect of tracking load on memory performance in Experiment 2 but not Experiment 3, where this aspect was eliminated by using only a single report on each trial. Even if some tendency to prioritise the tracking task remained in Experiment 3 due to the increased duration, salience or other aspect of the tracking display relative to the memory display, it was evidently not enough to cause any significantly detrimental effect of tracking load on memory performance. Alternatively, it is possible that the somewhat negative impact of tracking load on the memory task in Experiment 2 was because the task was more difficult due to the presence of the additional distractor objects in the tracking display. Distractor suppression during tracking appears to reduce tracking capacity (Bettencourt, & Somers, 2009) and targets can become confused with visually similar distractors (Drew, Horowitz, & Vogel, 2013). Furthermore, the greater the number of distractors, the more often they may come close to one another, causing negative effects of crowding on performance (Bae & Flombaum, 2012). It is not apparent from the current set of experiments which of these factors were responsible for the possible effects of tracking load on memory performance in Experiment 2, and future studies may wish to address these questions more directly. However, it is clear that in Experiment 3, when these factors were removed, any interference of this type was also eliminated.

Our results also do not clearly support a view in which spatial attention is used to support rehearsal of spatial working memory as has previously been proposed for other spatial memory tasks. Smyth and Scholey (1994) showed that shifts of spatial attention during the retention interval of a spatial memory task interfered with recall, indicating a role for attention in spatial rehearsal mechanisms. However, our findings do not support this view for encoding positions of targets since we find no detrimental effect of tracking on memory performance in Experiment 3. That is not to say that spatial attention cannot be used to facilitate spatial rehearsal, simply that is may not be necessary. Some have argued that the same mechanism of attention used for perceptual selection and processing is also responsible for post-perceptual processing and is in fact the same mechanism by which items are selected for maintenance in visual working memory (Awh, Vogel, & Oh, 2006; Chun, 2011). This account would seemingly predict much more severe interference in the dual tasks we present here. Much of the data used to support this highly unified account of visual attention and visual memory has used visual objects as stimuli with multiple features to be processed, necessitating the binding of features into object representations. Although we assessed position representations in the tracking task by means of colour probes in Experiments 1 and 2, Experiment 3 removed any non-spatial elements of the tracking task and revealed very little interference between the two tasks. In the paradigm presented here, where the tracking display was presented during the retention interval of the memory task, we were only able to assess interference with maintenance of representations in spatial memory, rather than their initial selection. It remains a possibility that attentional tracking and selection for entry into spatial working memory may rely on more similar processes than are demonstrated here for maintenance processes of spatial working memory.

In Experiment 3, the only apparent interference between tasks was in the frequentist analysis of the interaction between memory and tracking load on tracking performance. Here there was a greater effect of memory load when tracking one target than when tracking three, although no main effects were significant. One possible locus for this very moderate interference effect may be in a shared spatial priority map for both attention and memory. Hedge, Oberauer and Leonards (2015) previously suggested this as the site of interference between spatial attention and representations of multi-feature objects held and manipulated in working memory. Perhaps in Experiment 3 here, although the spatial memory and spatial attention tasks appear to draw on separate capacities, they may be represented in the same spatial map, leaving open the possibility for representations to interfere with one another though information crosstalk. As discussed by Pashler (1994) in regards to general sources of dual task interference, two concurrently carried out tasks can cause performance decrements on the basis of shared capacity-limited stages in processing, but the content of the information being processed may contribute to an additional source of interference. If representational content is similar for both processes, then representations may become degraded on the grounds of information conflict and not because they share core processes.

In summary, for spatial processing, the pattern of dual task interference we report here is not consistent with an account proposing shared core resources for visual spatial attention and spatial working memory. We also find no clear evidence for spatial memory processes being responsible for the magnitude of perceptual lags seen in the attentional position tracking task. Although spatial attention and spatial working memory are closely related processes and may interfere with one another under some circumstances, interference can be almost entirely eliminated. This suggests that interference between the two tasks is not due to them drawing on common core capacity-limited resources.

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Figure 1

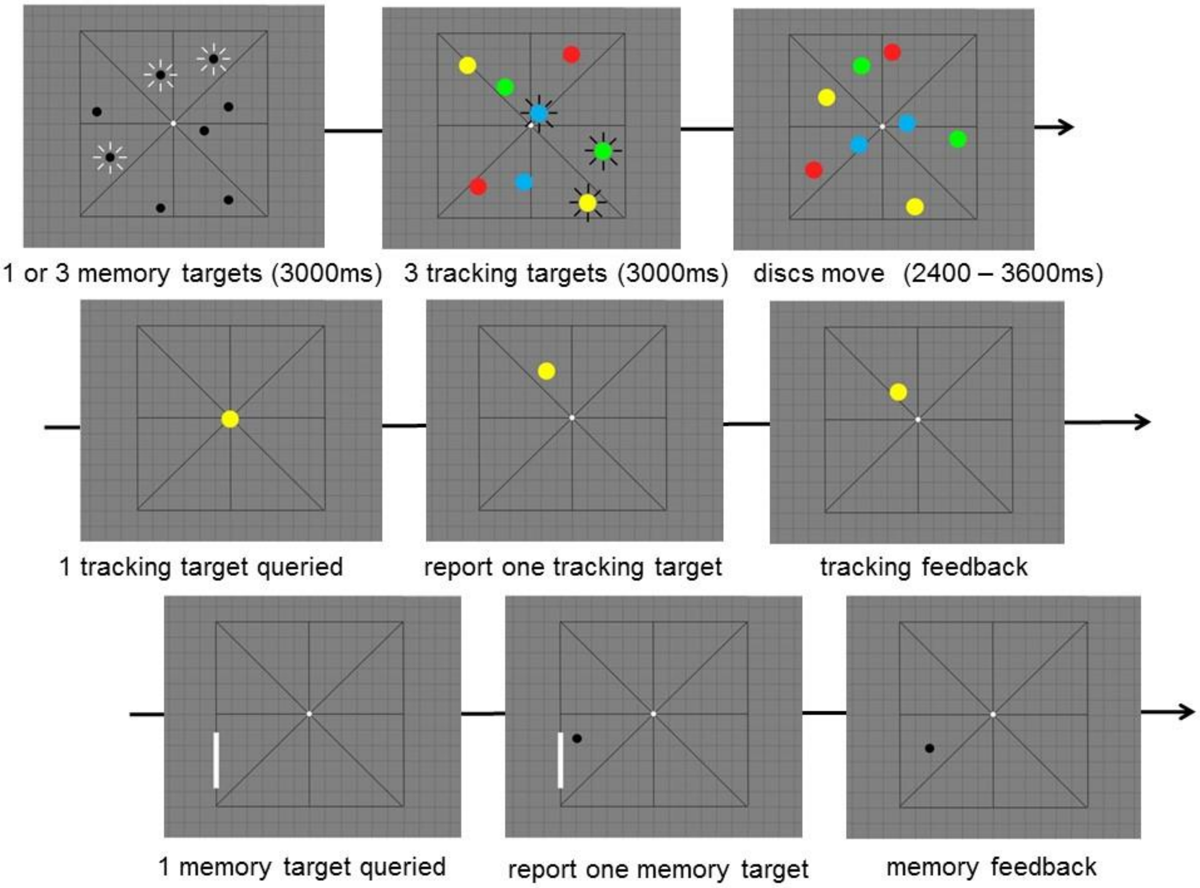


Figure 2

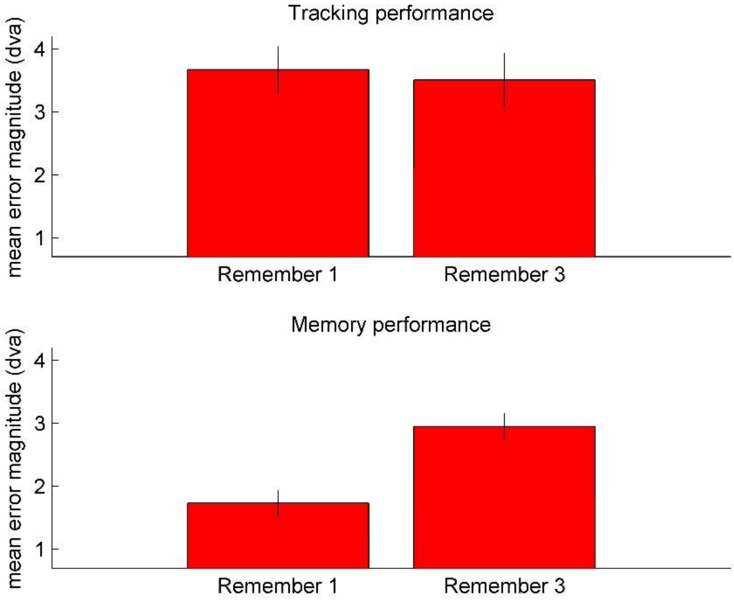


Figure 3

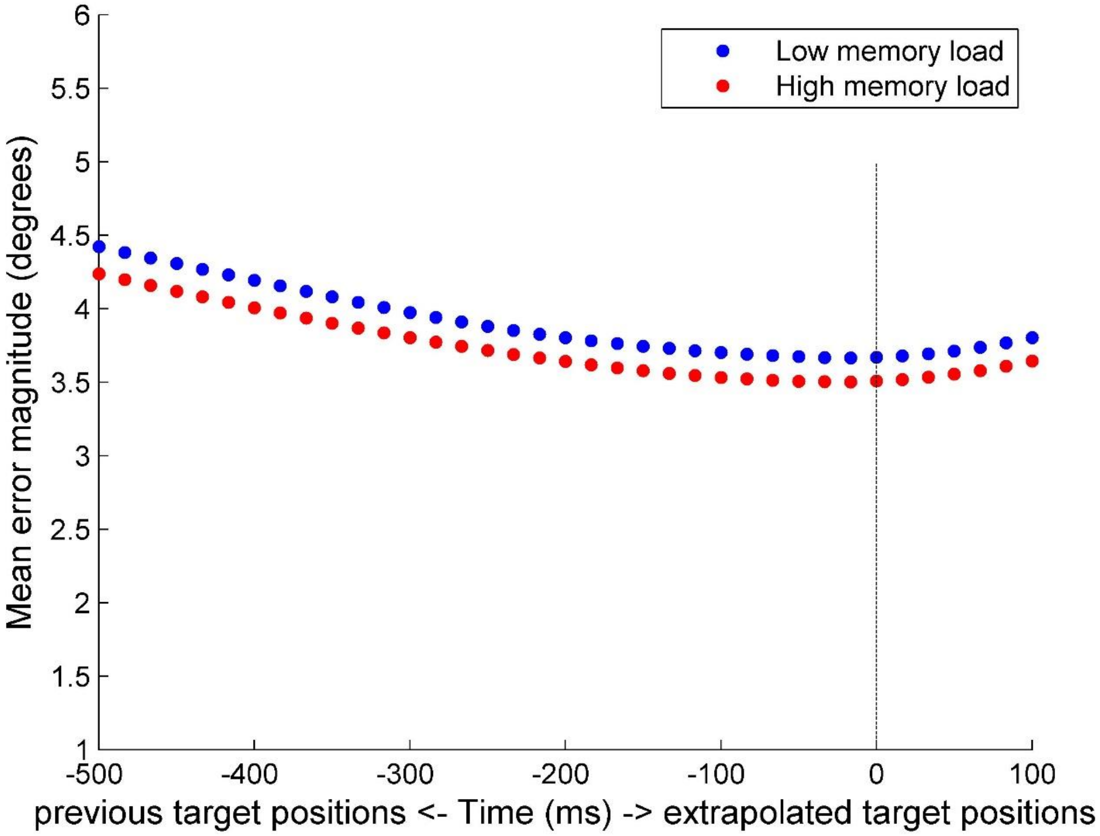
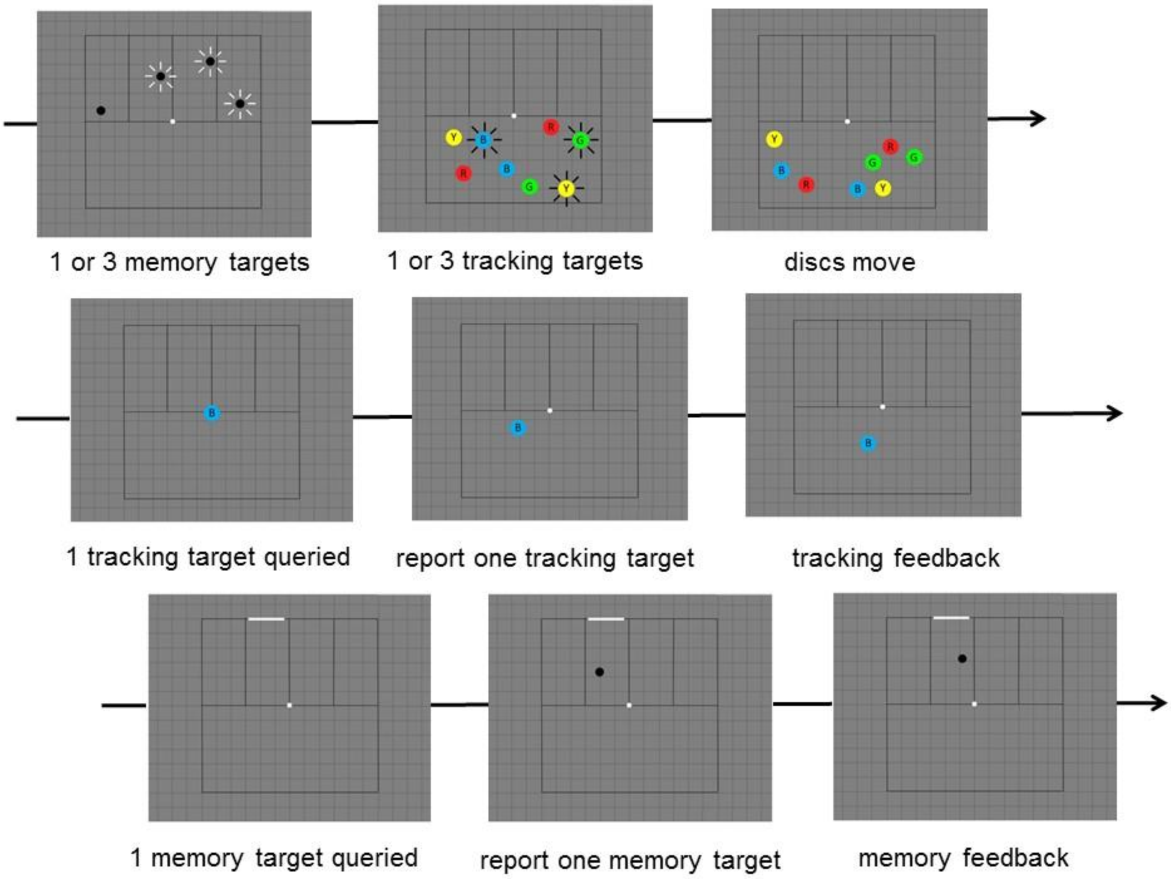

Low memory load
High memory load
Mean error magnitude (degrees)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
-500
-400
-300
-200
-100
0
100
previous target positions <- Time (ms) -> extracpolated target positions

Figure 4



1 or 3 memory targets

1 or 3 tracking targets

discs move

1 tracking target queried

report one tracking target

tracking feedback

1 memory target queried

report one memory target

memory feedback

Figure 5

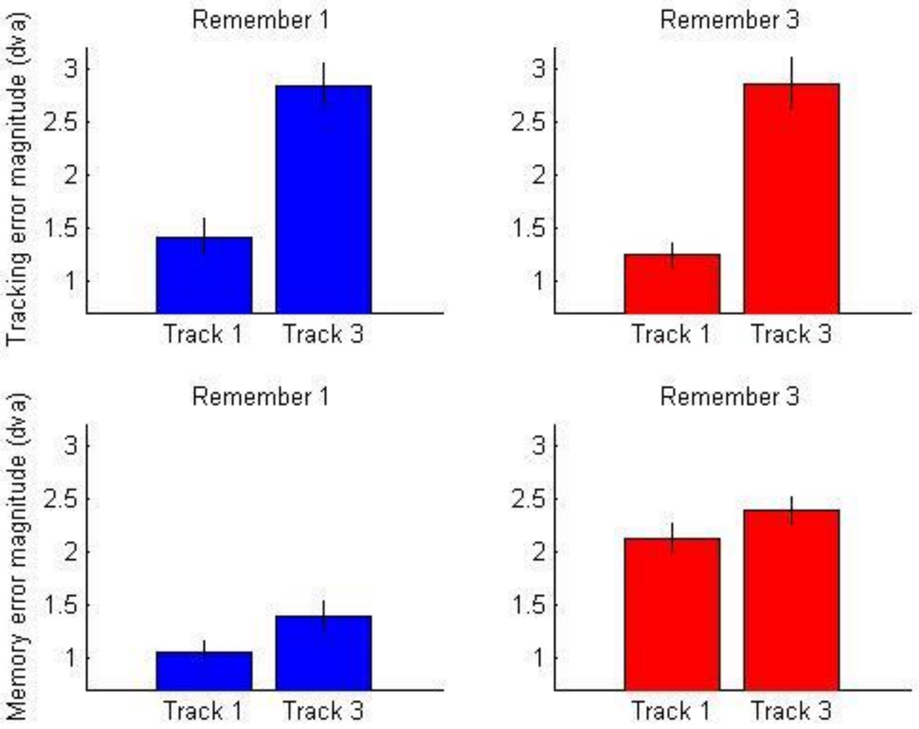

Remember 1
Remember 3
Tracking error magnitude (dva)
3
2.5
2
1.5
1
Track 1
Track 3
Remember 1
Remember 3
Memory error magnitude (dva)
3
2.5
2
1.5
1
Track 1
Track 3

Figure 6

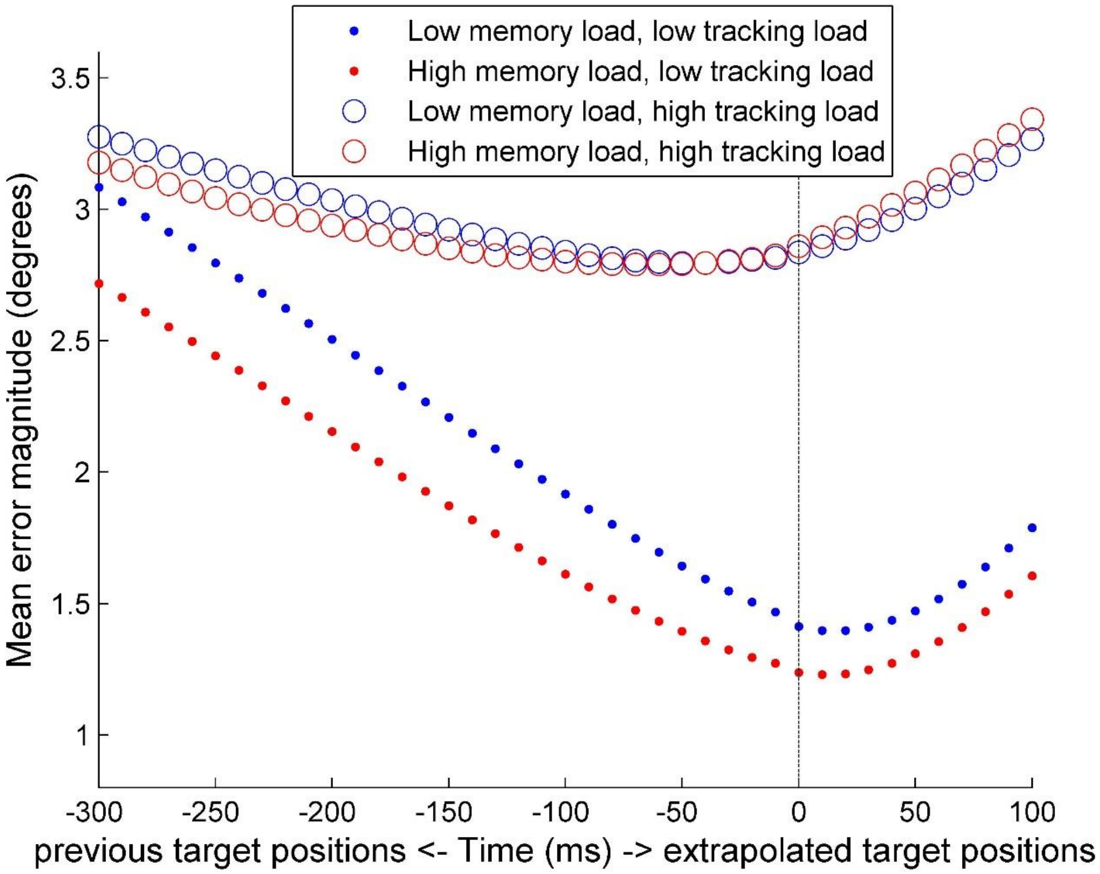
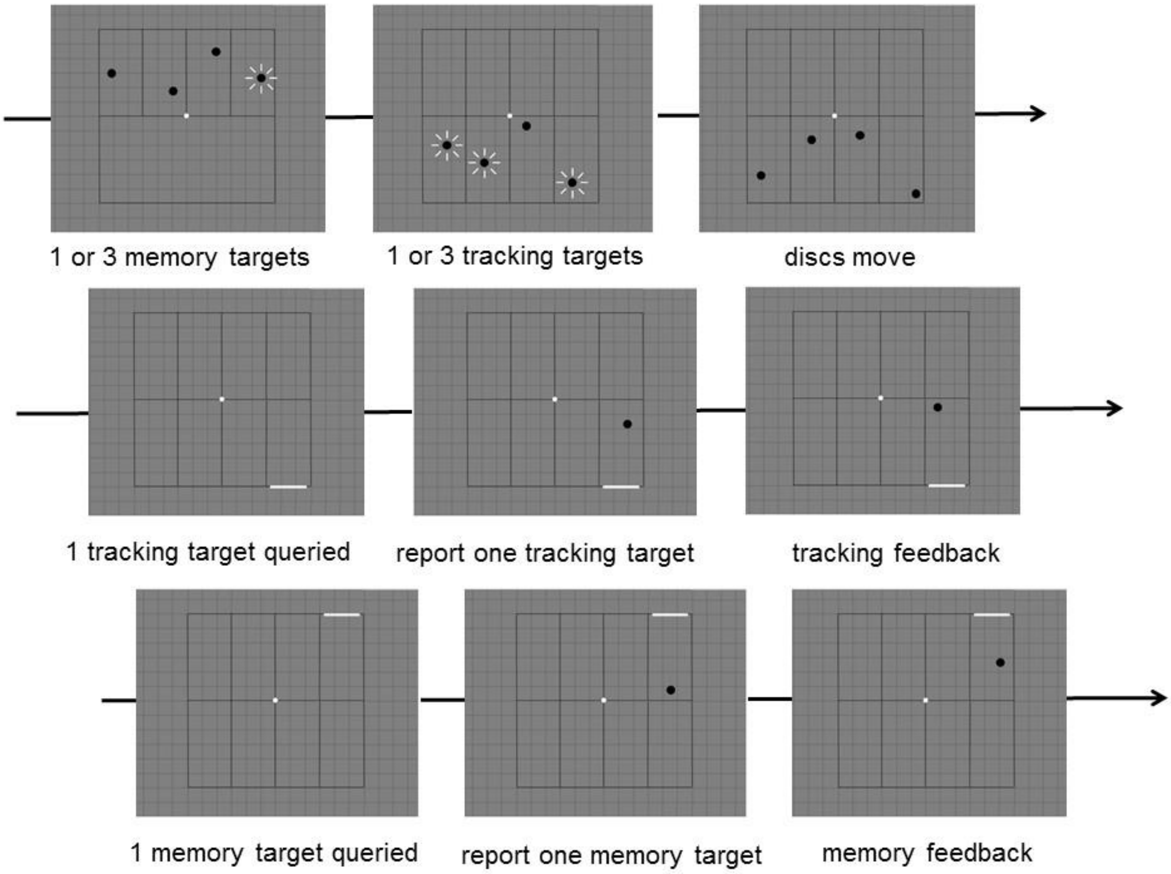

Low memory load, low tracking load
High memory load, low tracking load
Low memory load, high tracking load
High memory load, high tracking load
Mean error magnitude (degrees)
3.5
3
2.5
2
1.5
1
-300
-250
-200
-150
-100
-50
0
50
100
previous target positions <- Time (ms) -> extrapolated target positions

Figure 7



1 or 3 memory targets

1 or 3 tracking targets

discs move

1 tracking target queried

report one tracking target

tracking feedback

1 memory target queried

report one memory target

memory feedback

Figure 8

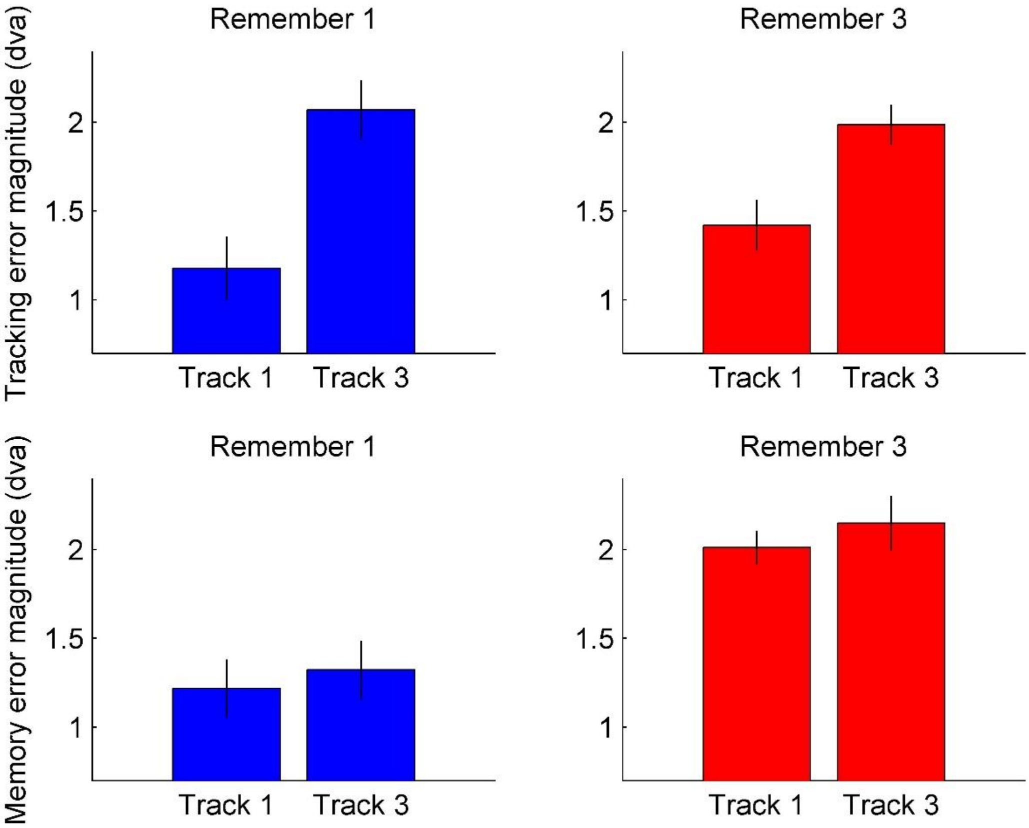
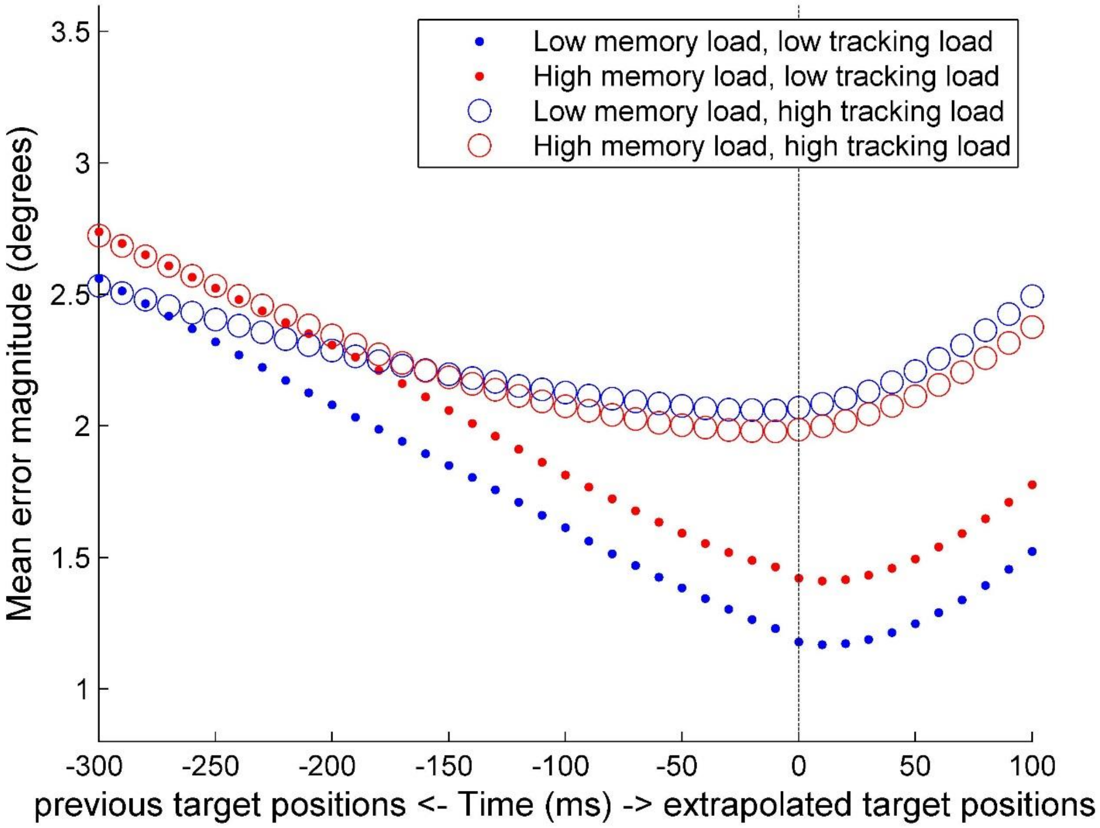

Remember 1
Remember 3
Tracking error magnitude (dva)
2
1.5
1
Track 1
Track 3
Remember 1
Remember 3
Memory error magnitude (dva)
2
1.5
1
Track 1
Track 3

Figure 9


Low memory load, low tracking load
High memory load, low tracking load
Low memory load, high tracking load
High memory load, high tracking load
Mean error magnitude (degrees)
3.5
3
2.5
2
1.5
1
-300
-250
-200
-150
-100
-50
0
50
100
previous target positions <- Time (ms) -> extrapolated target positions