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You detect while I search: examining visual search efficiency in a joint search task

Gerald P. McDonnell[a], Mark Mills[b], Jordan E. Marshall[b], Joshua E. Zosky[b] and Michael D. Dodd[b]

[a]Department of Psychology, McKendree University, Lebanon, USA; [b]Department of Psychology, University of Nebraska-Lincoln, Lincoln, USA

ABSTRACT
Numerous factors impact attentional allocation, with behaviour being strongly influenced by the interaction between individual intent and our visual environment. Traditionally, visual search efficiency has been studied under solo search conditions. Here, we propose a novel joint search paradigm where one individual controls the visual input available to another individual via a gaze contingent window (e.g., Participant 1 controls the window with their eye movements and Participant 2 – in an adjoining room – sees only stimuli that Participant 1 is fixating and responds to the target accordingly). Pairs of participants completed three blocks of a detection task that required them to: (1) search and detect the target individually, (2) search the display while their partner performed the detection task, or (3) detect while their partner searched. Search was most accurate when the person detecting was doing so for the second time while the person controlling the visual input was doing so for the first time, even when compared to participants with advanced solo or joint task experience (Experiments 2 and 3). Through surrendering control of one's search strategy, we posit that there is a benefit of a reduced working memory load for the detector resulting in more accurate search. This paradigm creates a counterintuitive speed/accuracy trade-off which combines the heightened ability that comes from task experience (discrimination task) with the slower performance times associated with a novel task (the initial search) to create a potentially more efficient method of visual search.

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Visual attention; visual search; working memory

Due to the capacity limitations of our attentional system, we are only able to process a subset of information in our visual environment at any given time (e.g., Cavanagh & Alvarez, 2005; Sears & Pylyshyn, 2000). As a result, it is critical that we ignore distracting information to focus on target items when operating in this complex world. Selective attention is thus an everyday occurrence, influencing behaviour both trivial – such as finding a friend in the stands at a football game – and significant – such as a radiologist detecting a cancerous tumour. Despite the fact that the purpose of the attentional system is to enhance processing efficiency, errors of attention occur often in complex tasks such as when the features of the target and distractor overlap (e.g., Duncan & Humphreys, 1989; Treisman & Gelade, 1980). As such, visual attention research tends to focus on how attention can be made to operate more efficiently. One oft-used paradigm for studying selective attention is visual search – wherein participants search for a target item amongst various distractors – given the relevance of this behaviour to a variety of everyday tasks (for a review, see Wolfe, 1994). For example, in the case of x-ray screening at airport terminals, one TSA agent is required to both search for and subsequently detect one or more targets embedded in luggage with other distracting non-threatening items. As a result, visual search is generally investigated as it relates to individual participants performing tasks on their own. It is not the case, however, that visual search is always a solo endeavour. Your friend may verbally or manually direct your gaze when searching for a sailboat through a set of binoculars; a radiologist may consult colleagues to get additional opinion on an x-ray: these types of scenarios are rarely studied within the context of the laboratory (see Brennan, Chen, Dickinson, Neider, & Zelinsky, 2008; Neider, Chen, Dickinson, Brennan, & Zelinsky, 2010). The purpose of the present study is to examine whether having one individual control the visual input of a second individual who is responsible for detecting a target improves detection efficiency as it relates to response time (RT) and accuracy.

CONTACT Gerald P. McDonnell gpmcdonnell@mckendree.edu Department of Psychology, McKendree University, 212 Carnegie Hall, Lebanon, IL 62254, USA

In solo search more so than joint search, the individual characteristics of the observer may introduce a top-down bias that is detrimental to one's task goals. For instance, utilizing a visual probe task, it has been shown that heavy drinkers are biased towards alcohol-related cues relative to social drinkers (Field, Mogg, Zetteler, & Bradley, 2004) and that smokers are biased toward smoking related cues (Ehrman et al., 2002). These biases in attention also extend to working memory, where individuals are more prone to interference when the contents of working memory share similar features to that of the distractors (Olivers, Meijer, & Theeuwes, 2006). Nonetheless, goal-driven attentional guidance is crucial in tasks that require the accurate and efficient search of difficult to find targets. In particular, consistency in search (i.e., scanning an image from left to right akin to reading a book) has been shown to facilitate the accurate identification of targets (Biggs & Mitroff, 2014). Though some argue for a memory free model of visual search (Horowitz & Wolfe, 1998, 2001, 2003), it is generally agreed that memory plays an important role in ensuring that we do not refixate previously examined locations of a scene (e.g., Beck, Peterson, Boot, Vomela, & Kramer, 2006; Dickinson & Zelinsky, 2005, 2007; Peterson, Kramer, Wang, Irwin, & McCarley, 2001). As such, consistency in search eliminates a degree of the cognitive burden associated with search such that it is unnecessary to remember locations previously fixated if the individual is scanning each image in a similar fashion. This is opposed to someone scanning an image in a random order (i.e., fixating on one random location and then directing search to another random part of the display), as resources are expended on remembering where one has previously searched (and/or implementing a search strategy) instead of on target detection. Memory resources expended in visual search tasks are associated with where one has previously fixated versus the individuating features of items in the visual field (Beck, Peterson, & Vomela, 2006; Oh & Kim, 2004; Woodman & Luck, 2004). As reducing one's cognitive burden has been shown to improve search efficiency (Cain & Mitroff, 2013), the alleviation of remembering previous locations fixated could be pivotal to successful performance in complex search tasks. In fact, recent work has led to the suggestion that individuals will complete a more difficult physical task to unburden working memory, termed "pre-crastination". Rosenbaum, Gong, and Potts (2014) had participants choose to move a bucket either a short or long distance to an alley's endpoint, which in turn meant that they would need to hold a critical task instruction (pick up and transport the bucket) in working memory for either a short or long period of time. Surprisingly, participants consistently chose the bucket closer to the start-point, and thus exerted greater physical effort relative to choosing the bucket near the end of the alley, which would be less physically taxing but more mentally taxing. It appears then that individuals will complete subgoals as quickly as possible to reduce working memory load in order to free up attentional space, allowing a focus on a primary goal (in this case walking to the end of the alley). In professions where the efficient search of target items has life-or-death consequences, it seems imperative then that one's working memory load is directed entirely towards the primary task goal(s). This is particularly the case in search tasks, where performance is heavily influenced by one's working memory load, shaping the way in which we select and prioritize stimuli in the environment (Downing, 2000; Olivers et al., 2006; Soto, Heinke, Humphreys, & Blanco, 2005).

Due to the various challenges presented in visual search tasks (i.e., problems of target visibility, oftentimes an unknown target set, multiple targets in a single search array, low target prevalence), previous work has aimed at improving search performance (Biggs & Mitroff, 2014). Menneer, Barrett, Phillips, Donnelly, and Cave (2007) found that multiple-target category search is inefficient when targets are defined by colour, shape, or orientation compared to single category search. Therefore, in the case of x-ray screening at airport terminals, more efficient search would result from multiple screeners searching for different target types (i.e., one agent searching for nonlethal items [liquids, aerosols, gels] and another agent searching for threat items [guns, knives]), where interference between target representations are mitigated and further attentional resources for target detection are available. Brennan et al. (2008) further demonstrated the effectiveness of multiple person search by having participants complete a simple visual search task (searching for the target "O" amongst various "Q" distractors) in pairs, where the trial would end as soon as one member of the pair responded to the target. Critically, participants were eyetracked, such that the gaze of one participant was superimposed over their partners' display and vice versa. Those working in pairs were more efficient compared to solitary searchers, with said pairs performing better on the task when verbal communication was prevented and only gaze location was shared. The value of collaborative search has also been demonstrated in a complex search task, where pairs of participants required a consensus before determining whether or not a target was present (Neider et al., 2010).

In the current study we sought to determine whether search performance would improve if one person scans a search array through a gaze-contingent window and, in doing so, controls the visual input of a second individual who identifies the target (Participant 1 controls the window via their eye movements and Participant 2 – in an adjoining room – sees only the stimuli that Participant 1 is directly fixating and responds to the target accordingly; see Figure 1 for a representation of the method). Though passing off the control of the visual input to another individual may seem difficult and/or unnatural, it does have the important benefit of reducing the memory load of the target detector given that they can now focus solely on a single task with little concern for search strategy and previously searched locations. Further, having two individuals responsible for successful task completion increases the accountability of the searcher, which may make them more thorough or efficient in search relative to when completing the task individually. The current study examines whether reducing the control of the observer, but with the trade-off of a reduced working memory load, results in more efficient and accurate search performance.

Joint search task

We were interested in determining how performance (in terms of speed and accuracy) on a detection task is altered when someone is searching for the target him or herself versus when another individual is in control of the visual input. We also examined the influence of task experience (Experiment 2). In Experiment 1, participants were instructed to determine whether a red square (the target) was present during each trial and respond via button press. Each display contained 32 squares and circles that were either red or blue, with eight items in each quadrant. Our stimuli were meaningless configurations to eliminate bias due to prior knowledge or expectations. The experiment consisted of three blocks of trials, with two potential trial orders (each block consisted of 164 trials). In Order 1: (Session A) Participant 1 performed the search task and target detection task individually, (Session B) Participant 1 then searched the display (e.g., controlled the gaze-contingent window) while Participant 2 detected the target, (Session C) Participant 2 then performed the same search and target detection task individually. In Order 2: (Session D) Participant 1 performed the search task and target detection task individually, (Session E) Participant 2 searched the display (e.g., controlled the gaze-contingent window) while Participant 1 detected the target, (Session F) Participant 2 performed the search and target detection task individually. The purpose of the two orders was to determine the influence of specific types of task experience on target detection task in the joint condition (see Figure 1 for a graphical depiction of paradigm and conditions). Moreover, this allowed us to examine whether search performance differs in joint vs. solo conditions.

Experiment 1

Method

Participants

A total of 80 undergraduate students from the University of Nebraska-Lincoln participated in the study and received course credit for their participation. Given that the task was completed in pairs, 40 participants (20 pairs) completed Order 1, while the remaining 40 participants (20 pairs) completed Order 2. All participants had normal or corrected-to-normal vision and were naïve to the purpose of the study that took place in a single 60-minute session.

Apparatus

The eye tracker was an SR Research Ltd. EyeLink II system (Mississauga, Ontario, Canada), with high spatial resolution and a sampling rate of 500 Hz. For all participants, the dominant eye was monitored. Thresholds for detecting the onset of a saccadic movement were acceleration of 8000°/s^2, velocity of 30°/s, and distance of 0.5° of visual angle. Movement offset was detected when velocity fell below 30°/s and

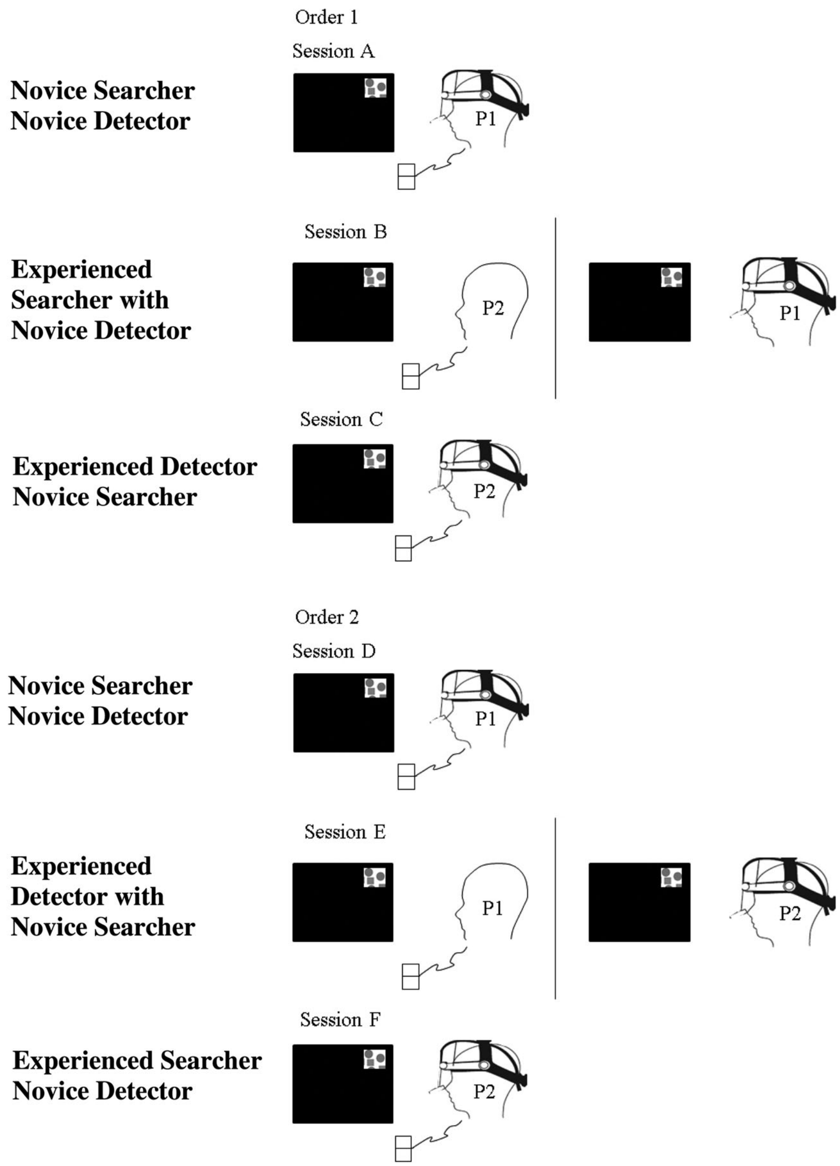

Figure 1. Illustration of the experimental setup and procedure in Experiment 1. In Order 1 Session A, Participant 1 performed the search task and target detection task individually. After completion, in Session B, Participant 1 controlled the visual input of Participant 2, while Participant 2 manually responded in the detection task. Finally, in Session C, Participant 2 completed the search and detection task individually. The identical procedure was used in Order 2, with the exception that, in Session E, Participant 2 controlled the visual input of Participant 1, while Participant 1 manually responded in the detection task.

remained at that level for 10 consecutive samples. The average error in the computation of gaze position was less than 0.5°. A nine-point calibration procedure was performed at the beginning of the experiment, followed by a nine-point calibration accuracy test. Calibration was repeated if any point was in error by more than 1° or if the average error for all points was greater than 0.5°. Participants completed the experiment on a Pentium IV PC, with a 60 Hz refresh rate, seated approximately 44 cm from the computer screen and made responses using both eye movements and the controller in front of them. Further, participants searched for the target through a gaze contingent window measuring $2° \times 2°$ visual degrees, such that participants could only see where they were fixating, with the remainder of the screen appearing black. During the joint search task, there was another Pentium IV PC that received input from the eye-tracking computer in an adjoining room where participants could only see where their counterpart was searching in the display. Participants in the adjoining room made responses with the controller in front of them seated approximately 44 cm from the computer screen.

Search display

Each display contained 32 squares and circles measuring 1° × 1° (a sample search display can be found in Figure 2). All displays have eight items in each quadrant but the displays were designed such that none of the stimuli could be viewed at fixation when the trial began to not influence the direction of the first eye movement. On no target trials (40% of trials), 16 of the squares were blue and 16 of the circles were red, divided evenly across the four quadrants. On target trials, one of the blue squares in one of the quadrants was replaced with a red square. Targets were evenly distributed across the four quadrants throughout the experiment where a target was present in a particular quadrant on 15% of the trials. Within a quadrant, the shapes varied in degree of proximity and in placement relative to one another, but no objects touched any other objects nor did any of the objects overlap the x or y axis. Within each quadrant, shapes were on average separated by .25°.

Order 1 procedure

The current experiment consisted of 492 trials divided evenly across three blocks, though each participant completed only two blocks (one individually and then one in the joint condition or vice versa; participants also completed 10 practice trials at the start of each block). Across blocks and participants, trial order was randomized. Figure 1 outlines the procedure described above, which we explain again here for clarity. In Block 1, Participant 1 was instructed to determine whether a red square (the target) was present during each trial and to respond with a controller utilizing their right-hand. Participants pressed one key for target present and another for target absent (no feedback was provided to participants regarding the accuracy of their response). RT represents the interval between the initiation of the trial and the eventual response (deciding whether a target was present). Participants were made aware that there was only one target on target present trials, and that the circle and squares presented in each of the four quadrants would vary in both number and location within the quadrants across trials. At the beginning of each trial, a fixation point appeared in the middle of the screen; participants were instructed to look directly at the fixation point and press the space bar to initiate each trial. Once the trial was initiated, the fixation point was removed and participants began searching through the gaze contingent window. Shape arrays were presented until a response was made (up to 12 s). This constitutes Session A. After the completion of Block 1, Participant 1 was instructed to complete the identical visual search task with the exception that Block 2 would involve working with a partner (Participant 2; this constitutes Session B) in an adjoining room that they could not communicate with. It was further instructed that Participant 1 would search for the target while Participant 2 would respond. Critically, Participant 2 only saw the visual input provided by Participant 1. Participant 2 was instructed to respond regarding the presence or absence of the target. As the searcher and detector saw the same visual input, both Participant 1 and Participant 2 were aware when a specific trial concluded (after a response was made the experimental display disappeared and the fixation cross reappeared). When Block 2 was complete, Participant 1 was debriefed while Participant 2 was calibrated on the eyetracker and completed the same search and target detection task individually (Session C).

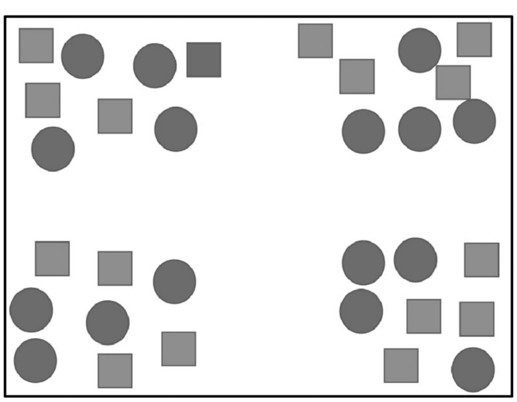

Figure 2. Example of the search array used in Experiments 1–3. Participants were searching for the target red square amongst red and blue circles and squares.

Order 2 procedure

As with Order 1, Participant 1 first completed the search task and target detection task individually (Session D). Unlike Order 1, however (in which Participant 1 continued to control the gaze-contingent window for a partner), Participant 1 then moved to the adjoining room and was tasked with detecting the target while Participant 2 was instructed to control the gaze-contingent window of Participant 1 (Session E). Finally, Participant 2 would then complete the same search and target detection task individually (Session F).

Results and discussion

As we are interested in how joint versus solo search alters performance (in terms of RT and accuracy) when responding to the target, our analysis includes both correct and incorrect trials (across conditions participants were incorrect on ∼5% of trials). Further, there were no observed differences in the results when excluding incorrect trials. One pairing of participants was deleted from the analysis in Order 1 due to an inordinately high error rate of 83% in the joint search condition. RTs less than 450 ms were considered anticipatory responses and were removed from the analysis (<2% of the trials).

Order 1 performance

A series of one-way ANOVAs were used to compare RT and accuracy when Participant 1 completed the target detection task individually versus when Participant 2 responded to the target while Participant 1 controlled the visual input (comparing Session A to Session B). We sought to determine then if joint search – where one individual with experience controlling the visual window and detecting the target (from Session A) searched for their counterpart detecting the target (in Session B) – resulted in improved performance compared to participants completing the task individually for the first time. This appears to be the case when examining RT (see Figure 3), where participants were significantly faster to respond to the target in the joint condition for target present trials, $F(1, 36) = 9.01$, $MSE = 506404.09$, $p < .01$. Participants were also faster in Session B to identify that the target was absent, $F(1, 36) = 6.59$, $MSE = 1978471.87$, $p = .02$. With regard to accuracy (see Figure 4), there was no difference in performance when comparing Participant 1 in Session A to Participant 2 in Session B for both target present, $F(1, 36) = 1.64$, $p = .21$, and target absent trials, $F(1, 36) = .82$, $p = .37$.

Next, it was of interest to determine whether the faster RTs (but no observed differences in accuracy) occurred in Session B relative to Session A due to experience with the task (Participant 1 was controlling the visual input for the second time in the joint condition), or because of factors related to two people completing the task under joint conditions (Experiment 2, detailed below, further examines the influence of experience on task performance). Specifically, a series of within-groups ANOVAs were utilized to examine how RT and accuracy differed when Participant 2 responded to the target in the joint condition versus when Participant 2 performed the search and target detection task individually (comparing Session B to Session C). In both scenarios, participants had experience with the task (Participant 1 was controlling the visual input for the second time in Session B while Participant 2 was detecting the target for a second time in Session C). The key difference though is whether search was under joint or solo conditions. For RT, there was no difference across conditions for both target present, $F(1, 18) = .29$, $p = .60$, and target absent trials, $F(1, 18) = .59$, $p = .45$ (see Figure 3). With regard to accuracy (see Figure 4), there was also no difference across conditions for both target present, $F(1, 18) = 1.02$, $p = .33$, and target absent trials, $F(1, 18) = 1.74$, $p = .20$. It seems then that task experience may have contributed to the faster RTs observed in the joint condition relative to when participants completed the task individually for the first time in Session A, as there were no significant differences in RT when comparing Session B to Session C.

Finally, we examined whether performance was best when completing the task individually without experience in Session A (Participant 1) compared to Session C, where Participant 2 completed the task individually but had experience detecting the target. Again, a series of one-way ANOVAs were utilized to compare RT and accuracy (comparing Session A to Session C). In terms of RT (see Figure 3) for target present trials, Participant 2 was significantly faster to respond to the target compared to Participant 1, $F(1, 36) = 7.46$, $MSE = 456273.34$, $p = .01$. This observed pattern was marginally significant for target absent trials, $F(1, 36) = 3.44$, $MSE = 2029964.46$, $p = .07$. For accuracy (see Figure 4), Participant 1 in Session A committed marginally less errors than Participant 2 in Session C for target present trials, $F(1, 36) = 3.67$, $MSE = .004$, $p = .06$. There was no significant difference in error rates for target absent trials, $F(1, 36) = .41$, $p = .53$. It appears then that completing the task

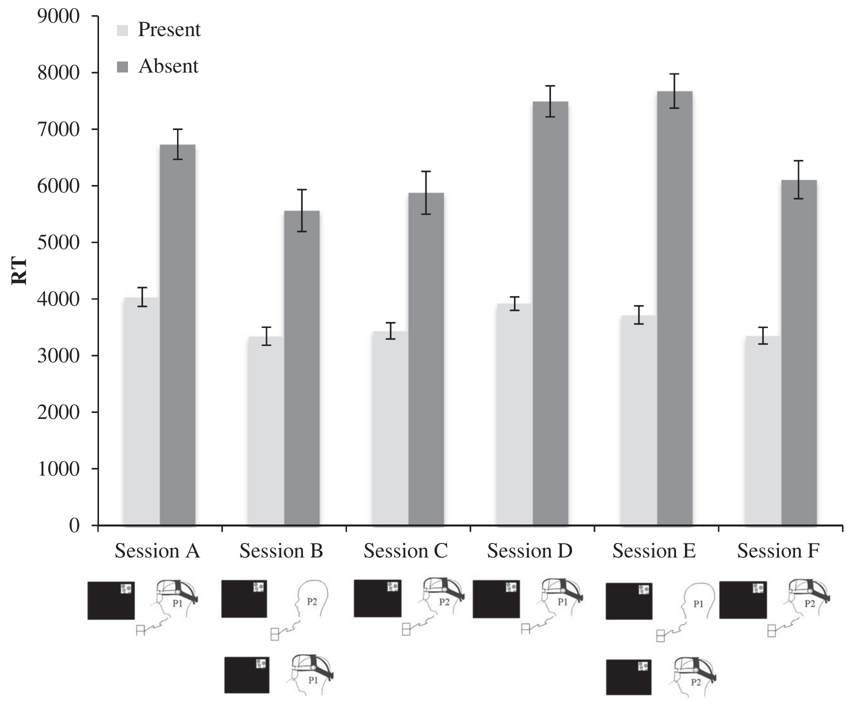

Figure 3. Response time as a function of condition and target type (present or absent) in Experiment 1. Error bars indicate the standard error for each estimate.

individually with experience detecting the target results in faster RTs, but with some degree of cost in terms of accuracy.

Overall, there were no informative differences present in accuracy across the three sessions of Order 1. Furthermore, though the joint condition led to faster response compared to individuals completing the task individually for the first time, this effect seems likely attributable to experience with the task given there were no observed differences in RT when comparing the joint condition to Session C. Nonetheless, in Order 1, the joint condition consisted of participants controlling the visual input for a second time. The purpose of Order 2 was to examine if joint search is more effective than individual search when participants in the joint condition detect the target for a second time. A summary of the critical comparisons between conditions for both Experiments 1 and 2 can be found in Table 1.

Order 2 performance

As with Order 1, we first sought to determine whether joint search influences target detection performance compared to when participants complete the task individually for the first time. Critically, in the joint condition of Order 2, the experienced participant was detecting the target, relative to Order 1 where the experienced participant in the joint condition was controlling the visual window. A series of within-groups ANOVAs were used to compare RT and accuracy when Participant 1 completed the target detection task individually versus when Participant 1 responded to the target while Participant 2 controlled the visual input (comparing Session D to Session E). For RT (see Figure 3), there was no difference across conditions for both target present, $F(1, 19) = .69$, $p = .42$, and target absent trials, $F(1, 19) = .32$, $p = .58$. However, with regard to accuracy (see Figure 4), Participant 1 in the joint condition made less errors compared to Participant 1 in Session D for both target present, $F(1, 19) = 4.98$, $MSE = .001$, $p = .04$, and target absent trials, $F(1, 19) = 7.69$, $MSE = .001$, $p = .01$.

We then examined whether the improvement in accuracy for the joint condition was the result of task experience or the nature of the joint search paradigm. To that end, a series of one-way ANOVAs were utilized to examine how RT and accuracy differed when Participant 1 responded to the target in the joint condition versus when Participant 2 performed the search and target detection task individually (comparing Session E to Session F). Though there was no difference in RT for target present trials, $F(1, 38)$

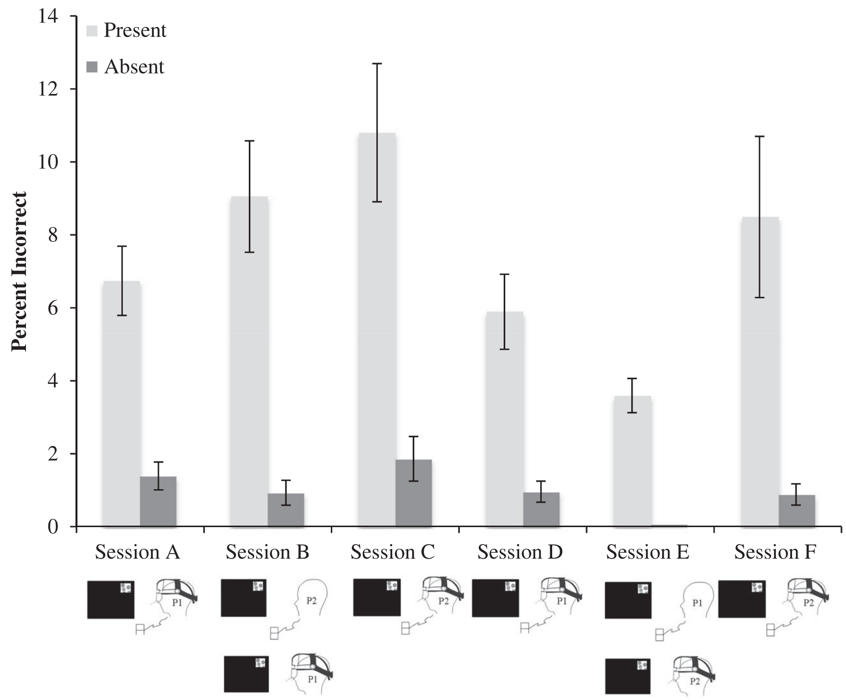

Figure 4. Percent incorrect as a function of condition and target type (present or absent) in Experiment 1. Error bars indicate the standard error for each estimate.

= .2.83, $p = .10$, Participant 2 in Session F was significantly faster to identify that the target was absent relative to Participant 1 in Session E, $F(1, 38) = 12.03$, MSE = 2040913.11, $p = .001$ (see Figure 3). More importantly, however, in terms of accuracy (see Figure 4), Participant 1 in Session E made fewer errors compared to Participant 2 in Session F for both target present, $F(1, 38) = 4.70$, MSE = .005, $p = .04$, and target absent trials, $F(1, 38) = 7.30$, MSE = .001, $p = .01$. It appears that task experience was most likely not the reason why superior accuracy performance was observed in the joint condition relative to individuals completing the task individually. It should be noted, however, that Participant 2 in Session F was not fully experienced with the task (in both scanning and detecting) compared to Participant 1 in Session E. Therefore, reduced accuracy in Session F compared to Session E could be influenced by whether an individual gained experience with the detection component of the task before completing it individually.

Table 1. Summary of comparisons across Experiments 1–3.

Comparison	Target Present RT	Target Absent RT	Target Present Errors	Target Absent Errors
A versus B	>	>	=	=
B versus C	=	=	=	=
A versus C	>	$>^{+}$	$<^{+}$	=
D versus E	=	=	>	>
E versus F	=	>	<	<
D versus F	>	>	=	=
B versus E	=	<	>	>
C versus E	=	<	>	>
T1 versus T2	>	>	=	=
T2 versus B	=	=	=	=
T2 versus E	<	<	>	$>^{+}$
JT1 versus JT2	>	>	=	>
JT2 versus E	<	<	>	>
JT1 versus T1	=	=	<	>
JT2 versus T2	=	=	=	>

Note: All arrows indicate a significant difference between the means being compared ($p < .05$) whereas = means no significant difference. For response time, > represents a slower response time for the first mean relative to the second whereas < represents a faster response time for the first mean relative to the second. For errors, > represents a greater number of errors for the first mean relative to the second whereas < represents a fewer number of errors for the first mean relative to the second. $>^{+}$ and $<^{+}$ indicates a marginally significant effect.

We were also interested in determining whether experience controlling the visual input in solo search resulted in improved performance relative to when participants were completing the task individually without experience. A series of one-way ANOVAs were used to compare RT and accuracy when Participant 1 completed the target detection task individually versus when Participant 2 completed the task individually (comparing Session D to Session F). Participant 2 in Session F was significantly faster to respond to the target compared to Participant 1 in Session D for target present trials, $F(1, 38) = 8.93$, MSE = 359758.549, $p < .01$. Participant 2 was also significantly faster to identify that the target was absent, $F(1, 38) = 10.18$, MSE = 1879520.03, $p < .01$ (see Figure 3). With regard to accuracy (see Figure 4), there was no difference across conditions for both target present, $F(1, 38) = 1.14$, $p = .29$, and target absent trials, $F(1, 38) = .00$, $p = .1.00$. Therefore, experience controlling the visual input unsurprisingly led to faster RTs compared to when participants completed the task individually without experience in Session D.

Comparisons in performance across Order 1 and Order 2

It was also of interest to determine whether performance differences were present across the joint conditions of Order 1 and Order 2 (comparing Session B to Session E). This comparison is informative since, in Order 1, Participant 1 was responsible for controlling the visual input (while the target detector was performing the task for the first time), while in Order 2, Participant 1 responded to the target for a second time (while the searcher was controlling the visual input for the first time). For RT, there was no difference across conditions for target present trials, $F(1, 37) = 2.75$, $p = .11$, Participant 2 in Session B was faster to identify that the target was absent relative to Participant 1 in Session E, $F(1, 37) = 19.68$, MSE = 2210101.66, $p < .001$. However, with regard to accuracy, Participant 1 in Session E was more accurate for both target present, $F(1, 37) = 12.18$, MSE = .002, $p = .001$, and target absent trials, $F(1, 37) = 6.30$, MSE = .001, $p = .02$. Having a novice control the window and someone with experience detecting the target appears to be an optimal search strategy, as participants in Order 2 were more accurate in target detection with a minimal cost to RT.

To further examine the effectiveness of Session E, we then compared performance data from Session E to Session C, where participants in both conditions had experience detecting the target, but were inexperienced in controlling the visual window. Specifically, in Session E, Participant 1 was paired with an inexperienced searcher whereas in Session C, Participant 2 completed the search task individually for the first time. Across conditions there was no difference in RT for target present trials, $F(1, 37) = 1.71$, $p = .20$. However, participants in Session C were faster to identify that the target was absent compared to participants in Session E, $F(1, 37) = 13.95$, MSE = 2260202.57, $p = .001$. With regard to accuracy, Participant 1 in Session E was more accurate for both target present, $F(1, 37) = 14.28$, MSE = .004, $p = .001$, and target absent trials, $F(1, 37) = 8.75$, MSE = .00, $p < .01$. Though both conditions had an experienced detector present and a novice searcher, participants in Session E outperformed those in Session C. This pattern of result suggests that joint search can result in greater accuracy compared to individual search, with no significant cost to RT.

Overall, joint search is more effective than solo search when the target detector in the joint condition is experienced with the task. Interestingly, experience does seem important as it relates to performing search under joint conditions, as performance was optimal in joint search when the target detector had experience with the task versus when the individual controlling the window had experience. Specifically, experience with the full task generally results in faster RTs when searching for the second time, and greater accuracy when detecting targets for a second time. This pattern of results seems reasonable as the target was randomly presented in one of four quadrants across the experiment. Therefore, there was no "correct" way to search for the target, and experience with search may even become detrimental due to a speeding-up of search with time. On the other hand, having experience detecting the target not only allows the individual ample familiarity with the target representation, but also experience with directing mental resources towards target recognition and not something like remembering previously fixated locations, which would be fruitless considering control of the visual window was forfeited.[1] Moreover, it is worth noting that an experienced detector may find it easier to learn and adapt to the visual behaviour of a novice searcher who is doing the task for the first time, as this individual is developing a search strategy of their own. An experienced searcher, on the other hand, has already developed their search strategy and implements it immediately which may make it more difficult for both novice and experienced detectors to adapt to. This could explain why joint search is not as efficient in Session B in which an experienced searcher controls the window for a novice detector.

Experiment 2

In Experiment 1, participants were most accurate detecting the target in the joint condition of Session E, where Participant 1 completed the detection task for the second time while Participant 2 was in control of the visual input for the first time. We drew support for this pattern of results when we compared Session E to Session F, where participants also had experience with the task, but searched and responded to the target individually. In the joint condition of Session E, however, Participant 1 had experience in both detecting and responding to the target, while in Session F, Participant 2 had experience of searching but not responding to the target (the same issue arises in our previous comparison of Session E to Session C). Therefore, the purpose of the current experiment is to further investigate the role of experience on task performance. Specifically, we sought to examine whether participants in Session E still exhibited superior performance in terms of accuracy compared to a scenario where participants completed two sessions of solo search, and thus were fully experienced with both aspects of the task.

Method

Participants

Eighteen undergraduate students from the University of Nebraska-Lincoln participated in the study and received course credit for their participation. All participants had normal or corrected-to-normal vision and were naïve to the purpose of the study that took place in a single 60-minute session. None of the participants had taken part in Experiment 1.

Apparatus and procedure

The procedure was identical to Session A and Session D of Experiment 1, with the exception that participants completed the identical search task for a second time individually rather than under a joint condition after the completion of the first session. Participants were provided with a brief break between sessions that was roughly equivalent to the time between sessions in Experiment 1.

Results and discussion

As in Experiment 1, our analysis includes both correct and incorrect trials (there were no observed differences in the results when excluding incorrect trials). RTs less than 450 ms were considered anticipatory responses and were removed from the analysis (<1% of the trials).

Task experience

It was first of interest to determine whether performance in terms of RT and accuracy improved with task experience. Specifically, we sought to determine whether participants showed improvements in task performance at Time 1 compared to Time 2, where they completed the task for a second time. In terms of RT (see Figure 5), participants were significantly faster to respond to the target in Time 2 compared to Time 1 for target present trials, $F(1, 17) = 35.40$, $MSE = 96489.29$, $p < .001$. Participants in Time 2 were also faster to identify that the target was absent, $F(1, 17) = 10.99$, $MSE = 416329.58$, $p < .01$. Critically however, in terms of accuracy (see Figure 6), there were no differences in performance when comparing Time 1 and Time 2 for both target present, $F(1, 17) = .001$, $p = .97$, and target absent trials, $F(1, 17) = .21$, $p = .65$. Therefore, it appears then that full experience with the task decreases RT, presumably due to a faster search strategy, but does not influence accuracy. Though participants had experience detecting the target, and gained familiarity of the target representation, this advantage disappears when also having to control the visual input, which presumably required them to remember previously fixated locations. This finding is identical to what was found in Experiment 1 when comparing Session D (identical to Time 1) to Session F (comparable to Time 2, with the exception that participants were experienced with only one aspect of the task). This pattern of results is also consistent with our previous comparison of Session A to Session B. It should be noted that the decrease in RT from Time 1 to Time 2 may be attributed to enhanced response resolution (Hout & Goldinger, 2012). Repeat exposure to target distractor configurations over time may have led to a more confident decision-making strategy, where less information was required for participants to respond to the target. Nonetheless, this possible enhanced searcher confidence did not influence accuracy across trials.

Experienced solo search versus joint search

It was next of interest to determine whether participants fully experienced with the task at Time 2

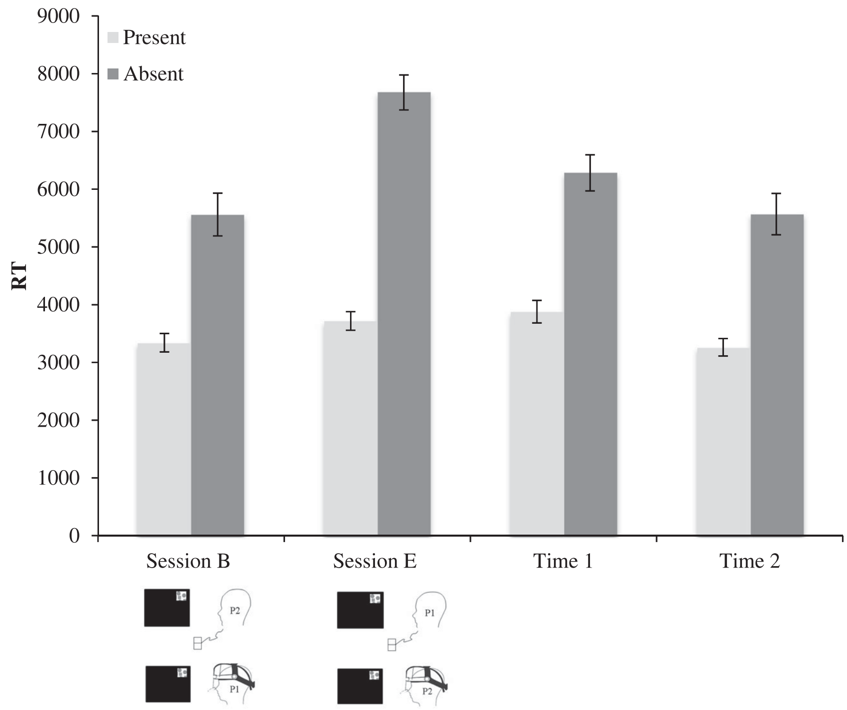

Figure 5. Response time as a function of condition and target type (present or absent) across the joint conditions of Experiment 1, and the data from Experiment 2. Error bars indicate the standard error for each estimate.

demonstrated superior performance relative to those in the joint conditions, where only one person was experienced with the task. When we compared performance in Session B (joint condition where the person controlling the visual window is doing so for the second time) to Time 2, there were no significant differences in terms of RT for target present, $F(1, 35) = .13$, $p < .73$, and target absent trials, $F(1, 35) = .00$, $p < .99$, or for accuracy on target present trials, $F(1, 35) = 1.01$, $p < .33$, and target absent trials, $F(1, 35) = .66$, $p < .43$. Though the joint condition of Session B had only one experienced individual performing the task, this pattern of results suggest that completing the task under joint conditions with an experienced searcher and an inexperienced detector does not improve task efficiency compared to fully experienced solo searchers.

Of greatest importance was our comparison of Time 2 to the joint condition of Session E. Here, we compare a joint condition where Participant 1 was fully experienced with the task, but Participant 2 was searching for the first time, to the fully experienced solo search condition. Participants were significantly faster to respond to the target at Time 2 compared to the joint condition of Session E for target present trials, $F(1, 36) = 4.23$, MSE = 463990.53, $p = .047$. Participants at Time 2 were also faster to identify that the target was absent, $F(1, 36) = 20.37$, MSE = 2062091.72, $p < .001$. Critically however, in terms of accuracy, participants in Session E made significantly fewer errors for target present trials compared to participants in Time 2, $F(1, 36) = 10.94$, MSE = 463990.53, $p < .01$, and for target absent trials, $F(1, 36) = 3.49$, MSE = 0.00, $p = 07$. Unsurprisingly, participants at Time 2 were faster to respond to the target as it was their second time controlling the visual window. Interestingly, though participants in Time 2 and Participant 2 in Session E were experienced detecting the target, those in the joint condition still showed superior accuracy. It appears that experience detecting the target is not as advantageous in search when individuals are still required to tag previously fixated locations in memory due to constraints in mental resources.

Experiment 3

The previous experiments demonstrated that an experienced detector paired with a novice in control of the visual input performed more accurately in a target detection task than solo searchers. However, it remains unclear whether the superior task performance found in Session E of Experiment 1 was

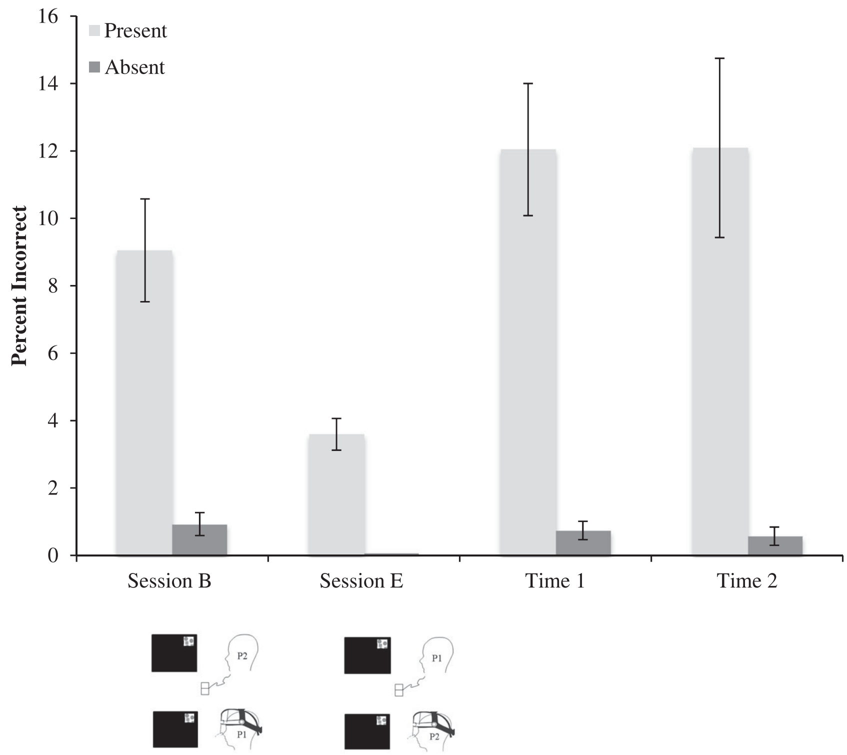

Figure 6. Percent incorrect as a function of condition and target type (present or absent) across the joint conditions of Experiment 1, and the data from Experiment 2. Error bars indicate the standard error for each estimate.

attributable to the reduced memory load of the detector, or whether it was attributable to their additional experience with the task (in Session E, the detector had always performed a solo search session prior to this critical session). To address this issue, in Experiment 3 we had pairs of participants complete two sessions of joint search wherein each individual maintained the same aspect of the task for both sessions (e.g., the searcher remained the searcher, the detector remained the detector). Though this does not permit us to compare solo to joint search in the same participant population, comparing the results of this experiment to the results of the previous two experiments will allow us to determine whether the improved accuracy in Session E of Experiment 1 was a function of a reduced working memory load for the detector vs. simply an effect of experience detecting whereas accuracy may improve with additional task experience.

Method

Participants

Fifty-two undergraduate students (26 pairs of participants) from the University of Nebraska-Lincoln participated in the study and received course credit for their participation. All participants had normal or corrected-to-normal vision and were naïve to the purpose of the study which took place in a single 60-minute session. None of the participants had taken part in the previous experiments.

Apparatus and procedure

Participants completed the same target detection task as in the previous experiments. However, in the current experiment a pair of participants arrived in the laboratory simultaneously, where one participant was randomly assigned to be the searcher and the other the detector. Participants completed the target detection task twice with their role as either searcher or detector unchanged across Time 1 and Time 2. Participants were provided with a brief break between sessions that was roughly equivalent to the time between sessions in the previous experiments.

Results and discussion

As in the previous experiments, our analysis includes both correct and incorrect trials (there we no observed differences in the results when excluding incorrect trials). RTs less than 450 ms were considered anticipatory responses and were removed from the analysis (<1% of the trials). Out of the 26 pairs, two sets of participants were removed from the analyses due to having RTs 2.5 standard deviations faster than the mean RT, however, the results reported below remained unchanged when including these participants.

The RT results are presented in Figure 7 and, as expected, participants were significantly faster to respond to the target at Time 2 relative to Time 1 for target present, $F(1, 23) = 7.73$, MSE = 145296.14, $p = .01$, and target absent trials, $F(1, 23) = 8.60$, MSE = 842040.99, $p < .01$. Critically however, in terms of accuracy (see Figure 8), there was no difference in performance when comparing Time 1 and Time 2 for target present trials, $F(1, 23) = .255$, $p = .62$. Participants were more accurate in Time 2 compared to Time 1 for target absent trials, $F(1, 23) = 5.62$, $p = .03$, though our critical finding in Experiment 1 related to target present trials only.

Though no changes in accuracy were observed for target present trials in this experiment, that alone does not tell us whether participants in the joint condition of Session E were more efficient in search compared to Time 2 of fully experienced joint search. Higher accuracy by participants in Session E would clearly demonstrate that it is the unburdening of working memory that is pivotal to efficient joint search and not just global practice with the task. Though participants in the present experiment were significantly faster to respond to the target at Time 2 compared to Session E for target present, $F(1, 43) = 5.84$, MSE = 394340.12, $p = .02$, and target absent trials, $F(1, 43) = 12.40$, MSE = 2180333.24, $p < .01$, the opposite was true for accuracy: participants in Session E made fewer errors for target present trials compared to participants in Time 2, $F(1, 43) = 17.10$, MSE = .002, $p < .001$, and for target absent trials, $F(1, 43) = 10.17$, MSE = 0.001, $p < .01$. Therefore, it appears that an experienced detector and novice searcher are more accurate on a target detection task compared to fully experienced joint or fully experienced solo searchers (Experiment 2).

Finally, it remains unclear whether a pair of novice or experienced joint searchers are more efficient in search compared to a novice or experienced solo searcher. When comparing inexperienced joint search in Time 1 to inexperienced solo search in Experiment 2, there were no differences in terms of RT for both target present, $F(1, 41) = 2.15$, $p = .15$, and target absent trials, $F(1, 41) = 1.87$, $p = .18$. Participants in the joint condition were more accurate in responding to the critical target present trials compared to solo searchers, $F(1, 41) = 3.37$, MSE = .004, $p = .07$, but the reverse pattern was found for target absent trials, $F(1, 41) = 7.39$, MSE = .006, $p = .01$. When comparing experienced joint search with experienced solo search, there were no significant differences in RT for both target present, $F(1, 40) = .001$, $p = .98$, and for target absent trials, $F(1, 40) = 1.21$, $p = .28$, as well as accuracy for target present trials, $F(1, 40) = 1.63$, $p = .21$. Participants were more accurate for target absent trials when experienced with solo search compared to joint search, $F(1, 40) = 5.38$, MSE = .001, $p = .03$. As such, it appears that joint search is only more efficient than traditional solo search under certain conditions. Specifically, it is beneficial to have a novice control the visual input versus an experienced participant, where optimal performance is not derived from differences in eye movements with experience, but instead the detector is gaining familiarly with target representation while simultaneously not having to devote resources to controlling fixations.

Discussion

In the present study we employed a novel paradigm where one individual controls the visual input of a second individual via a gaze contingent window during a target detection task to explore the relationship between joint search behaviour and detection performance. Though visual search is oftentimes carried out by multiple individuals (i.e., two friends searching for a car in a crowded parking lot), these dual search conditions are rarely studied within the laboratory context. Having participants forfeit control of search behaviour with a trade-off of a reduced working memory load resulted in enhanced detection performance. Specifically, in the joint condition of Session E, where Participant 1 completed the detection task for the second time while Participant 2 was in control of the visual input for the first time, participants were far more accurate when compared to the individual Order 2 task conditions and the joint condition of Session B. Experience with the task, specifically performing the detection task for a second

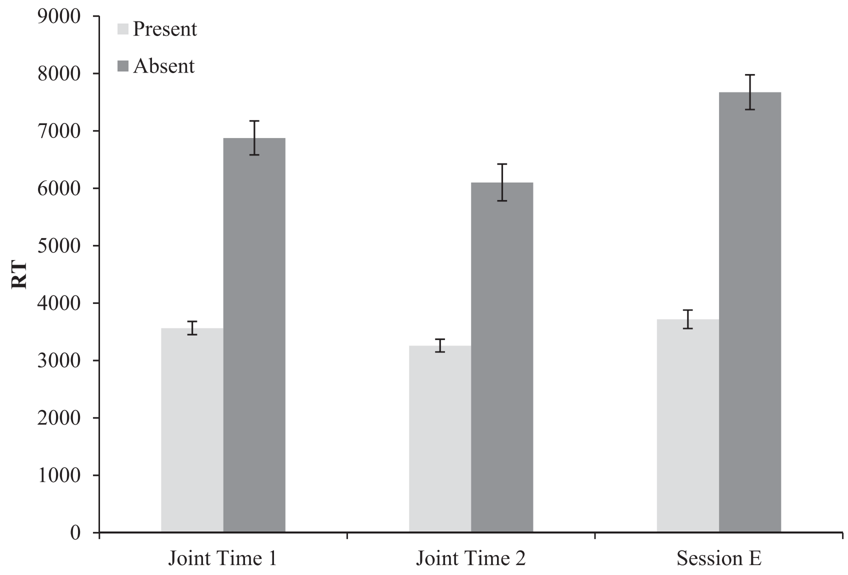

Figure 7. Response time as a function of time and target type (present or absent) in Experiment 3. Error bars indicate the standard error for each estimate.

time while having a novice control the visual window, results in the most accurate performance in the conditions tested. Moreover, it is important to note that this increase in accuracy was not accompanied by a large increase in RT relative to solo search in Experiment 1. This advantage in efficiency may be attributed to the experience of the target detector learning to direct precious mental resources solely towards target detection.

In Experiment 2, we examined the role of experience on task performance in solo search conditions only. Though faster to identify whether the target was present, there were no differences in accuracy between Time 1 and Time 2 when participants completed the same search task twice. Interestingly, though participants were experienced with detecting the target, and thus gained experience with target representation, this did not improve accuracy across

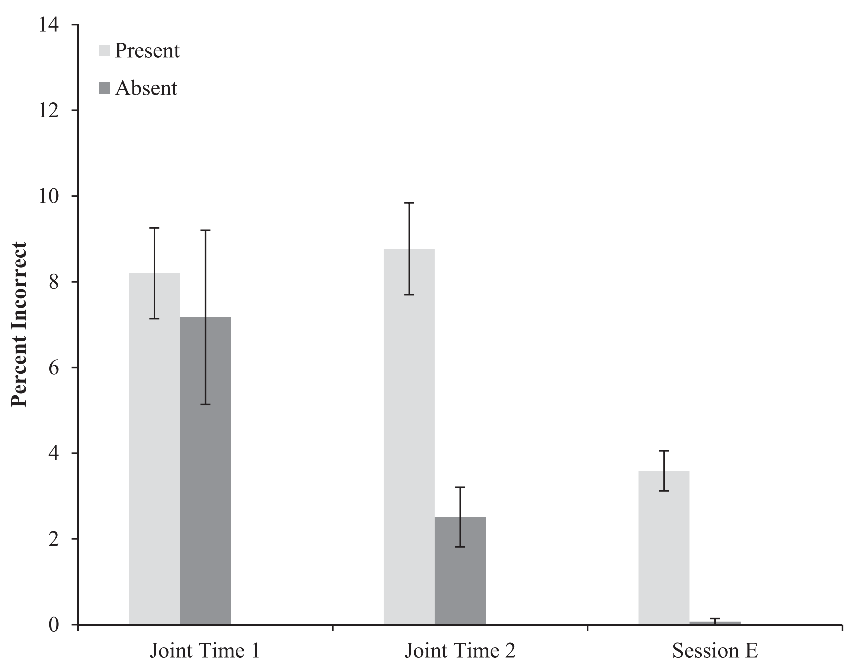

Figure 8. Percent incorrect as a function of time and target type (present or absent) in Experiment 3. Error bars indicate the standard error for each estimate.

time. This pattern of results is consistent with Order 1 of Experiment 1, where experience with the full task resulted in faster RTs but no differences in accuracy. Though faster RTs were observed when we compared Time 2 to Session E, participants in Session E were still more accurate despite only one participant having experience with the task. Counterintuitively, having a novice control the visual input is facilitatory, as the searcher may be less likely to initially exhibit a speeded search behaviour as they are becoming accustomed to the task. As such, the detector may find it easier to learn/adapt to the search strategy of a novice searcher. It is important to note, however, that our critical difference relates to target present trials and there is very little difference in RT on these trials across our joint and solo conditions. Our critical result, therefore, does not seem solely attributable to a speed/accuracy trade-off. A similar pattern of results also emerged in Experiment 3, where participants completed the same joint search task twice. Experience with the task did not influence accuracy on critical target present trials, again suggesting that simple practice is not driving our critical finding. Instead, it is the *combination* of an experienced detector (as shown in Session E) and inexperienced searcher (as shown when comparing Time 2 of joint search to Session E) that results in the most accurate search. Though participants were more accurate on target absent trials when experienced in the joint search task – potentially implying that experience factors into performance on target-absent trials – deciding whether a target is absent is much less pressing in reality: in radiology it is the detection of the presence and not the absence of a tumour that is important; in airport security it is the presence of dangerous/restricted items that is of primary concern.

The current study is the first to separate task responsibilities within a joint visual search task, wherein one individual is responsible for the search portion of the task and a second individual is responsible for the detection portion of the task. However, due to the importance of top-down information when conducting a search task (i.e., Bacon & Egeth, 1994; Theeuwes, 1992), the question remains whether it is possible to separate scan and detection behaviour. In the joint conditions (particularly in Order 1), where the person controlling the visual window also had experience detecting the target, it is unclear whether the searcher, who had no control of when a response was made, was also detecting the target. To address this question, we utilized a gaze-contingent window and a random array of target and distractor configurations across trials, where the searcher had no context information and as such there was no "best" way to search. As the salience of the display could not influence the top-down goals of the searcher, it seems unlikely that the searcher was also detecting. Work by McCarley, Kramer, Wickens, Vidoni, and Boot (2004) would suggest that, to some degree, these behaviours are separate, as practice does not improve both search and detection analogously (for an alternative account see Hout & Goldinger, 2015; Hout, Walenchok, Goldinger, & Wolfe, 2015).

A division of responsibilities results in improved accuracy for the joint condition of Session E. Though debated (see Horowitz & Wolfe, 1998, 2001), it is generally agreed that visual search requires some degree of working memory resources. For instance, individuals are unlikely to refixate previously examined locations during search, providing evidence that we use memory in order to bias attention towards novel locations and objects within a scene (i.e., Dodd, Castel, & Pratt, 2003; Klein & MacInnes, 1999; Mills, Van der Stigchel, Hollingworth, Hoffman, & Dodd, 2011). This suggests that what we are storing in memory is not necessarily the item's individuating features, but instead the location of the items in a search array (Beck, Peterson, & Vomela, 2006). Unsurprisingly then, when examining what factors predict accuracy in professional compared to nonprofessional searchers, it has been found that search consistency accounts for 35% of the variability in accuracy for professional searchers (Biggs, Cain, Clark, Darling, & Mitroff, 2013). If a searcher executes a repetitive pattern of eye movements across various search arrays, less mental resources are needed to remember locations previously searched and, as such, mental resources can then be redirected to other task demands (i.e., holding a template of the target in memory, motor response to the target). This seems of particular importance for difficult search tasks such as TSA agents scanning luggage for threat items. As threat items can take any number of forms (i.e., guns, knives, explosives) and are oftentimes difficult to detect due to variations in size and orientation, it seems pivotal that one's working memory be directed entirely towards object recognition. The current paradigm allows for a freeing up of mental resources for target detection due to the division of labour across responsibilities. Therefore, the person detecting the target needs only to compare the representation of the target in working memory to the shapes in the search array until a target match is found without the burden of remembering previously fixated locations or employing their own search strategy. This is of particular importance as search performance becomes inefficient when spatial working memory is full (Oh & Kim, 2004; Woodman & Luck, 2004). In the current study we observed the heightened ability that comes from task experience as it relates to detection paired with task inexperience as it relates to search to create a potentially more efficient method of visual search.

Future directions

Though we provide evidence that multiple person search is superior to solo search (see also Brennan et al., 2008; Neider et al., 2010), more work is needed to understand the efficiency of joint search, and the degree to which our presented paradigm can be applied to reality. Practically speaking, our findings offer promise for bettering the efficiency of career searchers in a variety of professional environments (e.g., TSA agents scanning luggage for threat items). However, the stimuli used in the current experiments were simple shapes, which is obviously a vast difference from the complexity of the real-world. Therefore, future work will be needed to determine whether an experienced detector and novel searcher paired together are still more effective in target detection utilizing complex stimuli. It is predicted that the effects demonstrated here would be ever more pronounced, as a larger working memory load is associated with searching complex scenes. Similarly, outside of the laboratory, oftentimes target detection is made extremely difficult, where the target is difficult to find, multiple targets are presented in an image, or the prevalence rate of the target is low. Therefore, future research is needed to explore whether joint search is effective under rare target conditions or when multiple targets are present in an image, and when targets have low salience and visibility. It is also a possibility that the size of the gaze-contingent visual window facilitated target detection to some degree, due to a reduction in visual clutter for both the solo and joint conditions. Future research can explore the ideal size of the window controlled by the observer to achieve optimal search efficiency. Finally, future research can address whether a searcher is a necessity in the current paradigm. Here we found that experience searching results in more errors in a target detection task compared to a novice controlling the visual input when paired with an experienced detector. Future research may address why such deterioration in performance for the searcher takes place with experience, and what factors can alleviate this decline. In a logistically simpler method, a single experienced detector could be shown small snapshots of the screen sequentially, and then decide from each individual snapshot whether the target is present or absent. Though a reduced working memory load would be observed for the target detector, we predict that this method would be inferior to the technique we propose as experience searching for the target was of importance, and something difficult to replicate with a computer program.

Note

1. We examined whether fixation duration (the length of time spent fixating a certain aspect of the visual scene) or saccade amplitude (the length of the eye movement) differed across conditions to determine if search became more efficient with experience. We also examined whether fixations durations were longer and if saccade amplitudes were shorter in the joint versus solo conditions. This eye movement pattern, signifying a slower search strategy, may be expected in a joint condition where one individual is responsible for the visual input of their counterpart. We had anticipated that this increase in accountability would lead the individual controlling the visual input to be more thorough and perhaps less efficient in joint search relative to when completing the task individually. However, there were no informative differences in the eye movement kinematics when comparing joint search versus when individuals searched for themselves. As a slower search strategy was not observed in the joint condition, our performance data cannot be attributed to a simple speed versus accuracy trade-off. Instead, the superior accuracy performance seen in Session E seems to occur due to a reduced working memory load of the target detector. This individual was not required to remember previously fixated locations as their counterpart was controlling the visual window and, as such, mental resources could be directed entirely towards detecting and responding to the target. Given that we did not observe any meaningful differences in fixation duration and saccade amplitude in

Experiment 1, we focused only on RT and accuracy in the subsequent experiments.

Disclosure statement

No potential conflict of interest was reported by the authors.

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