Psychonomic Bulletin & Review
2009, 16 (1), 116-120
doi:10.3758/PBR.16.1.116

No need for inhibitory tagging of locations in visual search

Johan Hulleman
University of Hull, Hull, England

Participants find it no harder to search for a T among Ls when the items move around at velocities of up to 10.8º/sec than when the items remain static. This result demonstrates that inhibitory tagging of locations is not necessary for successful search, and it provides a challenge to any models of visual search that use a fixed location as the index during accumulation and storage of information about search items.

In most theories of visual attention, and in theories of visual search in particular, the location of items plays an important role. For instance, in feature integration theory (Treisman, 2006; Treisman & Gelade, 1980), attention selects an item in the location map. The item's features are subsequently collected in an object file and bound (e.g., "red" and "horizontal" for a horizontal red bar). The activation map in Guided Search (Wolfe, 1994, 2007) is used in a similar way, although it combines bottom-up and top-down information. In the SAIM model (Heinke & Humphreys, 2003), a location map is used to represent the positions of items of attentional interest. In the SAIM model, the location map is also used in order to inhibit locations in the visual field once attention has moved away. Klein (1988) and Klein and MacInnes (1999) argued that inhibition of previously attended locations is a fundamental mechanism that facilitates difficult visual searches: Keeping track of inspected locations avoids revisiting them, making the search process more efficient. Müller and von Mühlenen (2000) and Takeda and Yagi (2000) reported evidence for Klein's (1988; Klein & MacInnes, 1999) hypothesis from probe experiments. Both groups suggested that inhibitory tagging was object based rather than location based, because inhibition was only observed when search items remained visible during the probe phase. There was no evidence for inhibitory tagging when items were switched off before probing. Müller and von Mühlenen suggested that the inhibitory system resets after scene changes. This would prevent inhibition of new objects appearing in previously inspected (and inhibited) locations.

Given the theoretical importance of item location, it was surprising when Horowitz and Wolfe (1998) reported that random relocation of search items every 111 msec yielded the same target-present slopes as did search among static items. This result seems to exclude inhibitory tagging of locations in visual search, because search should have been slower in the dynamic condition, either because of lingering inhibition from previous inspections or because search becomes less efficient when inhibition is continually reset.

However, there are problems with Horowitz and Wolfe's (1998) dynamic search paradigm. For instance, in the dynamic condition, objects come into and go out of existence every 111 msec, whereas the static condition contains no transients. Shore and Klein (2000) argued that transients benefited items in the dynamic condition (see Yantis & Jonides, 1984). Indeed, when Kristjánsson (2000) had items swap places rather than move to random locations, search slopes were steeper in dynamic displays. Furthermore, several authors (Shore & Klein, 2000; Takeda & Yagi, 2000; von Mühlenen, Müller, & Müller, 2003) suggested that participants might have attended to only part of the dynamic display, for limited amounts of time—replying *present* when the target appeared within this time, and *absent* otherwise. They found signs consistent with this sit-and-wait strategy in the results reported by Horowitz and Wolfe (1998). Target-absent slopes were much shallower in the dynamic condition than in the static condition. Furthermore, overall reaction times were much slower, and error rates considerably higher, in the dynamic condition. Von Mühlenen et al. forced participants to use the sit-and-wait strategy by making only part of the dynamic search display visible. Performance in these conditions was very similar to search in a dynamic display that was completely visible.

In response to these criticisms, Horowitz and Wolfe (2003) replicated their original results with displays in which items swapped places every 500 msec. However, error rates and intercepts in the dynamic displays were still higher than in the static displays. Moreover, since there was a target present on every trial, a comparison between target-present and target-absent slopes was not possible.

Although it might seem that the case for location-based inhibitory tagging has been made (Klein, 2000), the evi-

J. Hulleman, j.hulleman@hull.ac.uk

dence comes either from dual-task paradigms (Müller & von Mühlenen, 2000; Takeda & Yagi, 2000) or from sequential-search paradigms in which attention is cued to several locations before the search display appears, and search rates slow down when the target is positioned at a previously cued location (Snyder & Kingstone, 2000, 2007). Neither paradigm is entirely compatible with natural visual search. Conversely, random relocation suffers from its own incompatibility, because real-world objects move smoothly from location to location, rather than pop into and out of existence. It might therefore be better to use displays similar to those used in multiple-object tracking (MOT) tasks (Pylyshyn & Storm, 1988) in order to test inhibitory tagging of locations. In displays used in MOT tasks, multiple items move around smoothly, bouncing off display edges and each other.

In this experiment, we tested inhibitory tagging of locations in visual search by comparing a condition with static items (speed = 0.0º/sec) with conditions in which items moved with speeds of up to 10.8º/sec. There were no restrictions on the locations of items, other than that they remained within an (invisible) boundary rectangle and were not allowed to come within 1.45º of each other. If inhibitory tagging of locations is a necessary mechanism in visual search, search slopes under such conditions should increase with increasing speed. Using locations will become increasingly difficult, because items with greater speeds will cover longer distances and occupy more locations. Moreover, the chance of occupying a location that was previously occupied by another item becomes larger when speeds increase. All speeds were randomly intermixed.

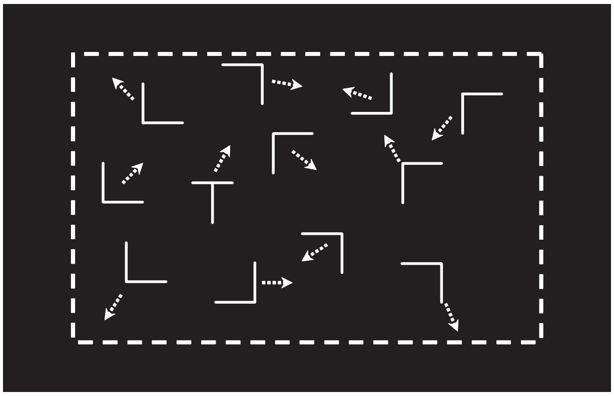

Figure 1. Illustration of the displays used in this experiment. Participants searched for a T among Ls. All items in a display moved with the same velocity in randomly chosen directions. Depending on the condition, velocity was either 0.0º, 3.6º, 7.2º, or 10.8º/sec. Items bounced off each other whenever they went closer than 1.45º or when they reached the edge of a virtual rectangle (29.0º × 19.3º, indicated by the dashed line).

METHOD

Participants

Sixteen students of Hull University (3 male, all right-handed; ages 18–25 years; average age = 20 years) participated in this experiment. All of the participants received course credit for their participation and were naive to the purpose of the experiment.

Stimuli

Ts and Ls (0.96º × 0.96º, white on a black background) were randomly positioned within a virtual rectangle (29.0º × 19.3º). Ts and Ls had four possible orientations: upright, or rotated −90º, 90º, or 180º. The minimum distance between items was 1.45º. All of the items in a display moved with identical velocity. Depending on the condition, velocity was 0.0º, 3.6º, 7.2º, or 10.8º/sec along a linear trajectory in a randomly chosen direction. Motion sequences consisted of 400 frames. In every frame, all items were shifted the appropriate number of pixels (0, 1, 2, and 3 pixels for 0.0º, 3.6º, 7.2º, and 10.8º/sec, respectively). Whenever the items reached the minimum distance from another item or reached the edge of the virtual rectangle, they bounced, and their trajectory changed according to an elastic collision. (See Figure 1.)

Procedure and Design

Stimuli were presented and responses recorded using software custom written in C++. Displays were presented on a 19-in. monitor (Iiyama Vision Master Pro 454; 800 × 600 pixels, 75 Hz) controlled by a GeForce 6800 graphics card. After a 1,000-msec blank display, a 0.5º × 0.5º fixation cross was presented for 500 msec in the center of the display. After offset of the fixation cross, the search display was presented. Each frame was presented for 13.3 msec. The displays contained 6, 12, or 18 items. The second factor was item speed: 0.0º, 3.6º, 7.2º, or 10.8º/sec. The task of the participants was to search for a T (present on 50% of the trials). The three factors (display size, target presence, and item speed) were fully crossed, yielding 3 × 2 × 4 = 24 cells for the analysis. Each cell contained 25 trials, giving a total of 600 trials.

The experiment started with 10 practice trials followed by 24 blocks of 25 randomly ordered experimental trials (all item speeds were intermixed). The participants used the "M" and "Z" keys of a standard U.K. keyboard to indicate *absent* and *present*. They used their preferred hand for *present* responses (i.e., they pressed the "M" key for *present* and the "Z" key for *absent* if they were right-handed).

RESULTS

The results are shown in Figure 2. A three-way Greenhouse–Geisser-corrected ANOVA (item speed × display size × presence) on reaction times yielded the expected main effects of display size (slower responses for larger display sizes) and presence (slower responses for absent trials), and there was a significant interaction between display size and presence (the larger the display size, the larger the difference between presence and absence) (all Fs > 36.8, ps < .001). More important, however, of the four effects involving item speed, only the main effect of speed [$F(3,45) = 22.2$, $p < .001$] and its interaction with presence [$F(3,45) = 4.5$, $p < .014$] were significant (other ps > .20). Reaction times increased when speeds increased, and this effect was more pronounced for target-absent trials than for target-present trials. Only for the highest item speed (10.8º/sec) did error rates increase.

Item speed lacked influence on search rates. Search slopes were ±17 msec/item for target-present and ±45 msec/item for target-absent trials for all item speeds. Moreover, the results lacked the controversial traits of those of Horowitz and Wolfe (1998). For instance, for the three conditions with moving items, slopes for target-

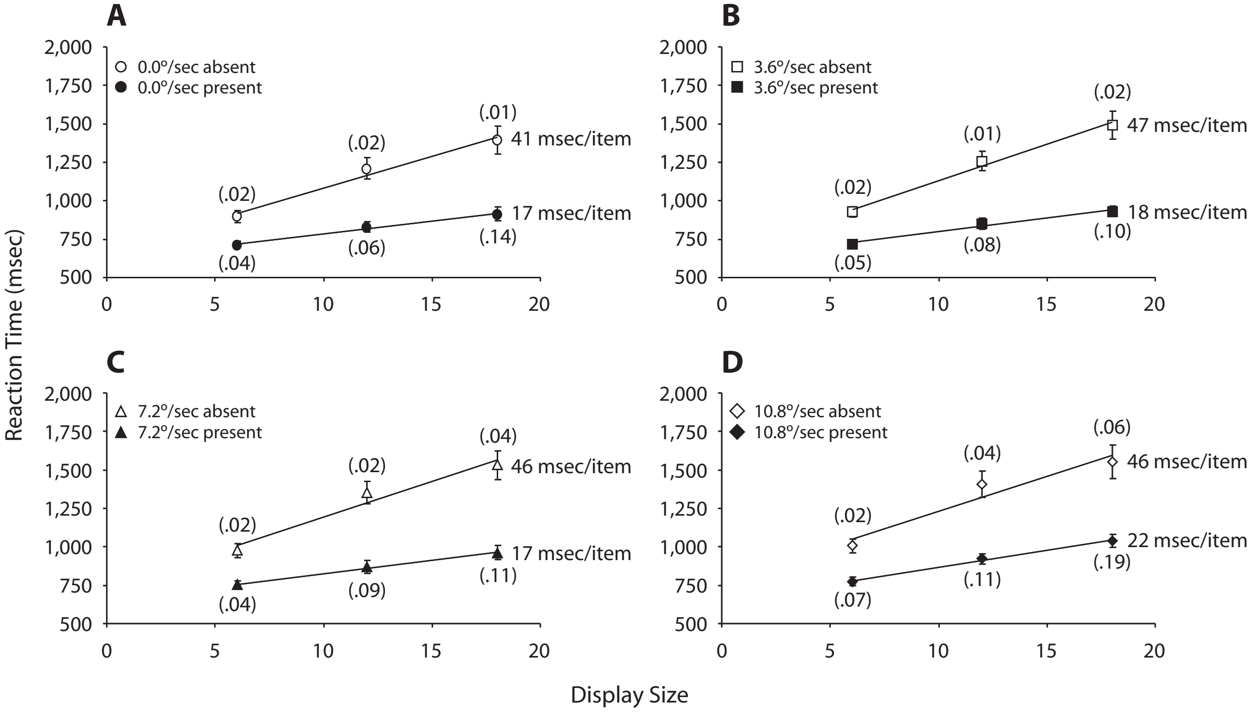

Figure 2. Reaction times as a function of display size. Open symbols are target-absent trials; black symbols are target-present trials. (A) Static items. (B) Item speed 3.6º/sec. (C) Item speed 7.2º/sec. (D) Item speed 10.8º/sec. The error proportions for each condition are shown in parentheses. The slope for each regression line is given to the right of the line. Error bars indicate standard errors; whenever error bars seem missing, they are covered by the data point.

absent trials were clearly steeper than those for target-present trials. Target-present and target-absent slopes resembled their counterparts for the static-item condition, rather than each other. This result provides one argument against the use of a sit-and-wait strategy (von Mühlenen et al., 2003) when items are moving. A second counterargument comes from the overall reaction times. Under a sit-and-wait strategy, the fastest items (10.8º/sec) would be expected to be found earlier, since they should move into any attended area more quickly. However, in this experiment, overall reaction times were slowest for 10.8º/sec. Furthermore, there were no real signs of a speed–accuracy trade-off. Error proportions were comparable in target-absent and -present trials up to 7.2º/sec. There was a slight increase for 10.8º/sec. Although this result could be taken as a sign of a speed–accuracy trade-off, it might reflect more general difficulties in recognizing the target, since error rates in the target-absent condition (i.e., false alarms) were increased too. Finally, overall reaction times were broadly comparable across all motion conditions, and the marginal increase in reaction time with increasing item speed probably again reflects general difficulties in target recognition.

A similar lack of influence of motion on search slopes has been reported before (von Mühlenen & Müller, 2000, Experiment 3). However, the range of speeds used (0º–3º/sec) was much smaller. Moreover, participants searched for an X among Os. This type of search is known to be very efficient when the items are static; von Mühlenen and Müller reported target-present and -absent slopes for their large-item size condition of 4.3 and 6.6 msec/item, respectively. Since inhibitory tagging of location is considered fundamental only for difficult searches, the result reported by von Mühlenen and Müller poses less of a challenge than does the independence of search slopes from item speed found here, because search for a T among Ls has been considered to require inhibitory tagging (e.g., Shore & Klein, 2000).

DISCUSSION

Items do not have to remain in the same location for visual search to work: Search slopes hardly increase for item speeds of up to 10.8º/sec. This result fits neatly with accounts of visual search that reserve only a minimal role for memory (e.g., Horowitz & Wolfe, 1998). Theories of visual search that use inhibitory tagging of locations (e.g., Klein, 1988; Klein & MacInnes, 1999), however, would have to be adapted in order to accommodate the results for the moving items.

One means of adaptation would be to assume that all of the information necessary for searching the display is extracted very rapidly, within the first 100–200 msec of exposure. During this time period, the displays used in this experiment are quite similar for all item speeds (the first frame is actually identical). If inhibitory tagging of locations is applied to a kind of stored representation of this information, the lack of influence of item speed would be accounted for. There is some evidence for early extraction of information. Dukewich and Klein (2005) reported that results were far above chance when participants had to report the orientation of a T among Ls, even at exposure durations as short as 60 msec. However, note that even at exposure durations as long as 480 msec, proportions correct were reduced relative to those for displays that remained visible until response. Moreover, Dukewich and Klein used static rather than moving items. Furthermore, this kind of account would seem to require that participants ignore the search display that is actually in front of them.

Another means of adaptation would be to assume that the inhibitory tagging is object based, so inhibition travels with the item. Object-based inhibitory tagging has been proposed before (e.g., Müller & von Mühlenen, 2000; Takeda & Yagi, 2000), but only in the sense that items should remain in existence. The tags were thought to be attached to the location of objects, rather than to the objects themselves (Kristjánsson, 2000).

How likely is inhibitory tagging of objects? The number of moving items used (up to 18) falls below the estimate of 20 items reported by Takeda (2004) as the memory capacity of visual search. (Other estimates are lower: According to Snyder & Kingstone, 2000, the limit is 5–6; according to Horowitz & Wolfe, 2001, 3–5.) However, these capacity estimates were obtained from experiments with static items. Memory capacity will probably fall when search items are moving. In an MOT experiment, Alvarez and Franconeri (2007) showed that the number of items that can be tracked drops from 8, when the items are moving very slowly, to 2, when item speeds are around 10º/sec. Furthermore, although inhibition of return has been reported for moving objects (e.g., Tipper, Weaver, Jerreat, & Burak, 1994), the number of objects used was a lot smaller, and the paths were considerably simpler than those used in the present experiment.

The lack of influence of the motion of items on search slopes provides a challenge for models of visual search. Even parallel models (e.g., Eckstein, Thomas, Palmer, & Shimozaki, 2000) are confronted with the need to determine which noisy signal belongs to which item when two or more feature dimensions are combined into a single response criterion. Either explicitly or implicitly, many models rely on the accumulation of evidence over time, using item location as an index. Whenever items are moving, especially at higher speeds, it will become harder to maintain the connection between the accumulating evidence and the item involved if only a location map is used. This should lead to a marked increase in errors with increasing speed. However, this was not found in our experiment. It might therefore be necessary to let go of simple notions of locations when visual search is concerned.

Note that the results reported here do not necessarily mean that search among static items does not rely on inhibitory tagging. Shore and Klein (2000) pointed out that simple similarity in search slopes and error rates for search among static and moving items is not enough to make this case. Moreover, substantial evidence for inhibitory tagging in visual search has been found in probe studies using static items (e.g., Müller & von Mühlenen, 2000; Takeda & Yagi, 2000).

It could be that inhibitory tagging occurs only when the items remain static; whenever the items are moving, other mechanisms support visual search. Under this account, the similarity in search slopes and error rates between static and moving conditions would be merely coincidence. However, it could also be that the inhibition of probes found in visual search among static items does not reflect inhibitory tagging. In this case, although there is inhibition, it does not actually influence search rates.[1] Either way, it seems that the representation of a search display used during visual search might be stranger and more powerful than has been previously imagined.

AUTHOR NOTE

Correspondence regarding this article should be addressed to J. Hulleman, Department of Psychology, University of Hull, Cottingham Road, Hull HU6 7RX, England (e-mail: j.hulleman@hull.ac.uk).

REFERENCES

ALVAREZ, G. A., & FRANCONERI, S. L. (2007). How many objects can you track? Evidence for a resource-limited attentive tracking mechanism. *Journal of Vision*, **7**(13, Art. 14), 1-10.

DUKEWICH, K. R., & KLEIN, R. M. (2005). Implications of search accuracy for serial self-terminating models of search. *Visual Cognition*, **12**, 1386-1403.

ECKSTEIN, M. P., THOMAS, J. P., PALMER, J., & SHIMOZAKI, S. S. (2000). A signal detection model predicts effects of set size on visual search accuracy for feature, conjunction, triple conjunction and disjunction displays. *Perception & Psychophysics*, **62**, 425-451.

HEINKE, D., & HUMPHREYS, G. W. (2003). Attention, spatial representation, and visual neglect: Simulating emergent attention and spatial memory in the selective attention for identification model (SAM). *Psychological Review*, **110**, 29-87.

HOROWITZ, T. S., & WOLFE, J. M. (1998). Visual search has no memory. *Nature*, **394**, 575-577.

HOROWITZ, T. S., & WOLFE, J. M. (2001). Search for multiple targets: Remember the targets, forget the search. *Perception & Psychophysics*, **63**, 272-285.

HOROWITZ, T. S., & WOLFE, J. M. (2003). Memory for rejected distractors in visual search? *Visual Cognition*, **10**, 257-298.

KLEIN, R. M. (1988). Inhibitory tagging system facilitates visual search. *Nature*, **334**, 430-431.

KLEIN, R. M. (2000). Inhibition of return. *Trends in Cognitive Sciences*, **4**, 138-147.

KLEIN, R. M., & MACINNES, W. J. (1999). Inhibition of return is a foraging facilitator in visual search. *Psychological Science*, **10**, 346-352.

KRISTJÁNSSON, A. (2000). In search of remembrance: Evidence for memory in visual search. *Psychological Science*, **11**, 328-332.

MÜLLER, H. J., & VON MÜHLENEN, A. (2000). Probing distractor inhibition in visual search: Inhibition of return. *Journal of Experimental Psychology: Human Perception & Performance*, **26**, 1591-1605.

PYLYSHYN, Z. W., & STORM, R. W. (1988). Tracking multiple independent targets: Evidence for a parallel tracking mechanism. *Spatial Vision*, **3**, 179-197.

SHORE, D. I., & KLEIN, R. M. (2000). On the manifestations of memory in visual search. *Spatial Vision*, **14**, 59-75.

SNYDER, J. J., & KINGSTONE, A. (2000). Inhibition of return and visual search: How many separate loci are inhibited? *Perception & Psychophysics*, **62**, 452-458.

SNYDER, J. J., & KINGSTONE, A. (2007). Inhibition of return at multiple locations and its impact on visual search. *Visual Cognition*, **15**, 238-256.

TAKEDA, Y. (2004). Search for multiple targets: Evidence for memory-based control of attention. *Psychonomic Bulletin & Review*, **11**, 71-76.

TAKEDA, Y., & YAGI, A. (2000). Inhibitory tagging in visual search can be found if search stimuli remain visible. *Perception & Psychophysics*, **62**, 927-934.

Tipper, S. P., Weaver, B., Jerreat, L. M., & Burak, A. L. (1994). Object-based and environment-based inhibition of return of visual attention. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 478-499.

Treisman, A. [M.] (2006). How the deployment of attention determines what we see. *Visual Cognition*, **14**, 411-443.

Treisman, A. M., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology*, **12**, 97-136.

von Mühlenen, A., & Müller, H. J. (2000). Perceptual integration of motion and form information: Evidence of parallel-continuous processing. *Perception & Psychophysics*, **62**, 517-531.

von Mühlenen, A., Müller, H. J., & Müller, D. (2003). Sit-and-wait strategies in dynamic visual search. *Psychological Science*, **14**, 309-314.

Wolfe, J. M. (1994). Guided Search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, **1**, 202-238.

Wolfe, J. M. (2007). Guided Search 4.0: Current progress with a model of visual search. In W. D. Gray (Ed.), *Integrated models of cognitive systems* (pp. 99-119). Oxford: Oxford University Press.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception & Performance*, **10**, 601-621.

NOTE

1. I thank Steve Luck for this suggestion.

(Manuscript received May 6, 2008;
revision accepted for publication July 29, 2008.)