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Balancing energetic and cognitive resources: Memory use during search depends on the orienting effector

Grayden J.F. Solman *, Alan Kingstone

University of British Columbia, Vancouver, BC, Canada

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ABSTRACT

Search outside the laboratory involves tradeoffs among a variety of internal and external exploratory processes. Here we examine the conditions under which item specific memory from prior exposures to a search array is used to guide attention during search. We extend the hypothesis that memory use increases as perceptual search becomes more difficult by turning to an ecologically important type of search difficulty – energetic cost. Using optical motion tracking, we introduce a novel head-contingent display system, which enables the direct comparison of search using head movements and search using eye movements. Consistent with the increased energetic cost of turning the head to orient attention, we discover greater use of memory in head-contingent versus eye-contingent search, as reflected in both timing and orienting metrics. Our results extend theories of memory use in search to encompass embodied factors, and highlight the importance of accounting for the costs and constraints of the specific motor groups used in a given task when evaluating cognitive effects.

1. Introduction

Increasingly often, the distinction is made between *Visual Search* as a particular cognitive paradigm (Treisman & Gelade, 1980), and human *search behavior* more generally (Hollingworth, 2012). Visual search has been the subject of considerable research, and is in many ways quite well understood and successfully modeled (e.g., Itti & Koch, 2000; Wolfe, 1994, 2007). In contrast, the field of research examining general search behavior remains nebulous, faced with the familiar challenges of embodied cognition – to understand the ongoing interplay between internal cognitive processing and the constraints and affordances of the material environment (Clark, 1999; Glenberg, 2010; Wilson, 2002). As the scope of search is extended beyond the initial moments of sensory processing, there is reason to believe that the relative contributions of and tradeoffs between internal processing (e.g., memory and prediction) and external exploration (e.g., attentional shifting, eye-movements, body movements) may shift from what is observed in more 'dis-embodied' laboratory tasks. For instance, Gilchrist, North, and Hood (2001) had participants perform an embodied foraging task, where search items were embedded in film canisters distributed throughout a room – so that searchers had to walk through the space to inspect items. Compared to purely oculomotor search, they found a reduced rate of item revisits, suggesting an increased role for memory of the locations inspected – though it could not be determined whether this reflected memory for specific items, or a consequence of more systematic search paths.

Changes across tasks in the relative weighting of internal and external processing have been proposed to reflect an optimizing principle, so that the relative *costs* of cognition as compared to orienting and sensation will determine the proportionate reliance on these modes for a given task. For instance, when participants are copying patterns of

* Corresponding author. Address: BAR Lab – Department of Psychology, University of British Columbia, Vancouver, BC V6T 1Z4, Canada. Tel.: +1 6048220069.

E-mail address: grayden@psych.ubc.ca (G.J.F. Solman).

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blocks from a model, they routinely check the model twice for each block – once to determine which color to acquire, then again after a suitable block has been found to determine where it should be placed in the copy (Ballard, Hayhoe, & Pelz, 1995; Ballard, Hayhoe, Pook, & Rao, 1997). This pattern indicates a preference to use knowledge 'in-the-world' (i.e., the model) over knowledge 'in-the-head' (i.e., working memory), as the latter case predicts at most one model-check per block, to determine both the necessary color and position. Studies of change detection during a block-sorting task in virtual reality have also been used to determine the extent and timecourse of working memory use during sorting (Droll, Hayhoe, Triesch, & Sullivan, 2005). In this context, participants were found to store a block's characteristics in working memory when it was picked up, but routinely failed to notice changes to these features prior to the sorting decision – typically sorting instead on the basis of the pre-change feature. Subsequent work indicated that task predictability and memory load played a crucial role in determining whether participants relied on working memory or a 'just-in-time' strategy whereby item features were queried from the environment only just before they were needed (Droll & Hayhoe, 2007). The authors concluded that the data reflect "*some kind of optimization or trade-off with respect to a set of constraints on the part of the observer*," though what specifically was being optimized remained unclear.

Several findings implicate a role for the effort associated with using external information stores in determining this trade-off. In the block-copying task described above, when the model was placed farther away from the participant, necessitating larger orienting movements, the amount of model checking was reduced (Ballard et al., 1995). Similarly, when solving arithmetic problems, the amount of note taking during intermediate steps is influenced by the availability of the note taking apparatus (Cary & Carlson, 2001). In a study where participants prepared to write a report from text-based sources, the likelihood of printing out a page of information was reduced when the printing process was made more complicated and time-consuming (Schönpflug, 1986). Finally, in a computer based puzzle-solving task, participants relied more on planning and less on exploratory manipulations of the puzzle when those manipulations required the input of lengthy commands (O'Hara and Payne, 1998). All of these results are consistent with the notion that increasing the effort needed to acquire information 'in-the-world' promotes an increased reliance on internal cognitive processes.

One concrete proposal, the 'soft constraints hypothesis,' holds that it is solely temporal costs that are being minimized, via behavioral selections occurring every 500–1000 ms (Gray & Fu, 2004; Gray, Sims, Fu, & Schoelles, 2006), adopting the commendably explicit position that "*milliseconds matter and they matter the same regardless of the type of activity with which they are filled*". There is reason, however, to doubt the exclusivity of temporal costs. In particular, a time-only model fails to account for the kinematics of the perceptuo-motor actions involved in using knowledge 'in-the-world'. In contrast, a large body of work in the domain of motor control has evaluated the optimization criteria for movement, and has routinely implicated the importance of minimizing such factors as 'jerk' (acceleration transients; Hogan, 1984), torque change (Uno, Kawato, & Suzuki, 1989), and metabolic energy expenditure (Sparrow & Newell, 1998). Composite utility models including kinematic factors as well as time generally show a 'knee' region, such that a reasonable tradeoff between time and kinematic cost exists up to a point (the 'knee'), but as time is further reduced to its minimum, kinematic costs rapidly increase (Nelson, 1983). Indeed, even in the context of traditional orienting behaviors, recent work successfully reproducing eye movement dynamics with a model using a weighted tradeoff between time-optimal and minimum energy criteria, found that as movement size increased, the contribution of time-optimality became negligible (Wang & Hsiang, 2011). Since naturalistic tasks typically involve a full suite of effectors with varying kinematic properties, the results summarized above suggest that energetic cost may often have an equal or larger influence than time expenditure in the control of naturalistic behavior.

Search behavior provides a valuable context for investigating internal–external resource tradeoffs, as the information being sought in a search task is the *location* of a target, a qualitative distinction from task contexts that involve referencing information from a constant known position (c.f. '*perceptuo-motor search*' vs. '*perceptuo-motor access*'; Gray & Fu, 2004). Conceptually, it is akin to the difference between checking the time by looking at your watch and checking the time by finding a clock in an unfamiliar room. In the former case, relying on the external environment has an effectively constant orienting cost (i.e., aligning your eyes to your wrist). In the case of search, however, the energetic effort associated with relying on knowledge 'in-the-world' (i.e., searching anew each time) will increase with both the physical scale of the search space and the number of objects it contains.

To date, existing studies of repeated search through identical or nearly-identical displays have examined only relatively low-cost forms of orienting (i.e., gaze-fixed, or eye-movements only; Kunar, Flusberg, & Wolfe, 2008; Oliva, Wolfe, & Arsenio, 2004; Solman & Smilek, 2010; Võ & Wolfe, 2012; Wolfe, Klempen, & Dahlen, 2000). These studies have found that memory for specific item locations provides a relatively weak source of guidance in typical search contexts, although increased memory benefits have been found both for more eccentric targets and for search requiring more difficult perceptual discrimination (Solman & Smilek, 2012). In contrast, orienting during naturalistic search involves not just eye-movements, but also head- and trunk-movements, manipulation of the environment, and movement of the body through space (Foulsham, Walker, & Kingstone, 2011). If internal processing and external exploration trade off on the basis of relative energetic cost, the differential recruitment of effectors in different search contexts may have important consequences for the use of memory, so that search necessitating the use of a costly effector like the head should increase the propensity to use memory when compared to search needing only much cheaper eye-movements.

The present research explores the degree to which minimization of energetic cost might explain the selection of