

Perceptuomotor incoordination during manually-assisted search

by

Grayden J. F. Solman

A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Doctor of Philosophy
in
Psychology

Waterloo, Ontario, Canada, 2012

© Grayden J. F. Solman 2012

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The thesis introduces a novel search paradigm, and explores a previously unreported behavioural error detectable in this paradigm. In particular, the ‘Unpacking Task’ is introduced – a search task in which participants use a computer mouse to sort through random heaps of items in order to locate a unique target. The task differs from traditional search paradigms by including an active motor component in addition to purely perceptual inspection. While completing this task, participants are often found to select and move the unique target item without recognizing it, at times continuing to make many additional moves before correcting the error. This ‘unpacking error’ is explored with perceptual, memory load, and instructional manipulations, evaluating eye-movements and motor characteristics in addition to traditional response time and error rate metrics. It is concluded that the unpacking error arises because perceptual and motor systems fail to adequately coordinate during completion of the task. In particular, the motor system is found to ‘process’ items (i.e., to select and discard them) more quickly than the perceptual system is able to reliably identify those same items. On those occasions where the motor system selects and rejects the target item before the perceptual system has had time to resolve its identity, the unpacking error results. These findings have important implications for naturalistic search, where motor interaction is common, and provide further insights into the conditions under which perceptual and motor systems will interact in a coordinated or an uncoordinated fashion.

Acknowledgements

I am grateful in particular to my advisor, Daniel Smilek, for his relentless optimism and consistent direction, and to Allan Cheyne for many fruitful and engaging discussions. I am also thankful to my committee members, Britt Anderson and James Danckert, for their valuable comments and advice, and to the research assistants who have aided in this project: Brandon Ralph, Trish Varao Sousa, Nicholas Wu, Vivian Cheng, Kaitlyn Gahagan, and Sandy Vuong. This work was supported by NSERC.

Table of Contents

Author's Declaration	ii
Abstract.....	iii
Acknowledgements	iv
Table of Contents	v
List of Figures.....	vi
1. Introduction	1
2. The Experiments.....	9
2.1 Experiment 1	11
2.2 Experiment 2	19
2.3 Experiment 3	24
2.4 Experiment 4	39
2.5 Experiment 5	54
2.6 Experiment 6	59
2.7 Experiment 7	70
2.8 Error Rates and Set Size: Meta-analysis	77
3. General Discussion	78
3.1 The Unpacking Error	78
3.2 Relation to Documented Errors	81
3.3 Concluding Comments	85
Appendix A Trace Computation – Experiment 3	87
Bibliography	89

List of Figures

Figure 1.1 Neisser’s Perceptual Cycle. Adapted from Neisser (1976).	2
Figure 1.2 Expanded Perceptual Cycle as applied to search behaviour.....	4
Figure 1.3 Expanded Perceptual Cycle for search, highlighting the novel component of active exploration.	7
Figure 2.1 Sample displays for the Dissimilar item set (A) and Similar item set (B). Participants were instructed to locate the target item, displayed in the green box on the right, and to drag it onto the green target box.....	13
Figure 2.2 Search items composing the Similar stimulus set.	14
Figure 2.3 Response Times (seconds) for Experiment 1, plotted across Set Size for Similar items (solid line) and Dissimilar items (dashed line). Error bars depict one standard error of the mean.....	17
Figure 2.4 Proportion of trials having Caught errors (trials where the target was moved twice in succession, with the second move being to the target box) and Uncaught errors (trials where the target was moved at least twice, with at least one intervening non-target move) in Experiment 1. Values are plotted across Set Size for Similar items (solid line) and Dissimilar items (dashed line). Error bars depict one standard error of the mean.	18
Figure 2.5 Response Times (seconds) for Experiment 2, plotted across Set Size for search under Load (solid line) and No Load (dashed line) conditions. Error bars depict one standard error of the mean.	22
Figure 2.6 Proportion of trials having Caught errors and Uncaught errors in Experiment 2. Values are plotted across Set Size for search under Load (solid line) and No Load (dashed line) conditions. Error bars depict one standard error of the mean.	23
Figure 2.7 Example display from the Yoked-vision condition in Experiment 3. Each item was displayed only as a blank grey card unless it had been selected. The identity of a selected card was visible only while the mouse button was depressed. The target template was always visible.	26
Figure 2.8 Response Times (seconds) for Experiment 3, plotted across Set Size for search under Yoked-vision (dashed line) Full-vision (solid line) conditions. Error bars depict one standard error of the mean.	28
Figure 2.9 Proportion of trials having Caught errors and Uncaught errors in Experiment 3. Values are plotted across Set Size for search under Yoked-vision (dashed line) and Full-vision (solid line) conditions. Error bars depict one standard error of the mean.	31
Figure 2.10 Characteristics of mouse movements for trial-terminating target moves on correct trials, plotted for Full-vision and Yoked-vision conditions. The dashed line indicates the total velocity of the	

movement (in degrees per second), while the solid line indicates the component of this movement in the direction of the response box. Positive values indicate movement toward the response box, and negative values indicate movement away from the response box. Shading represents the significance level for a t-test against zero. 32

Figure 2.11 Characteristics of mouse movements for erroneous target moves on Caught and Uncaught error trials, and for a comparison non-target move on correct trials (Standard) plotted for Full-vision and Yoked-vision conditions. The dashed line indicates the total velocity of the movement (in degrees per second), while the solid line indicates the component of this movement in the direction of the response box. Positive values indicate movement toward the response box, and negative values indicate movement away from the response box. A value at zero indicates movement orthogonal to the direction of the response box. Shading represents the significance level for a t-test against zero. 35

Figure 2.12 Distribution of error severity for Uncaught errors (indexed by the number of intervening moves between initial and final movement of the target), plotted for Yoked-vision (dashed line) and Full-vision (solid line) conditions. Error bars depict one standard error of the mean. * $p < .001$ 38

Figure 2.13 Proportion of Trials in Experiment 4 having Caught errors (solid line) and Uncaught errors (dashed line), plotted across Set Size. Error bars depict one standard error of the mean. 42

Figure 2.14 Data alignment procedure for eye-tracking samples. Samples were aligned relative to individual moves. The Recording Space (left) refers to the native on-screen coordinate system. Within the Recording Space, each move defined a vector from the grab location to the drop location. This vector was taken as the positive y-axis for Plotting space, and samples were reflected about this axis. All samples surrounding a given type of move (e.g., first target move on Uncaught error trials) were translated into this common reference frame and then averaged into traces. The resulting ‘Plotting Space’ can be understood as follows. The starting position for a move is at the origin, and the drop position is at some positive distance up the y-axis. Negative values on the y-axis indicate movement in the opposite direction from the actual move. The x-axis has only positive values, and represents distance orthogonal to the movement vector. 43

Figure 2.15 Mouse (left) and Eye (right) movement traces relative to the final, trial-terminating target move on correct trials (refer to Figure 2.14 and text for description of the plotting space). The grey disc and enclosed rectangle at the origin indicate the starting position of the target, while the empty disc and enclosed rectangle at the top left of each plot indicate the drop position of the target (for these moves, this is the response box). Traces are plotted for the period prior to the movement (1) and

for the period during the movement itself (2). Numbered circular markers indicate the beginning time points for each trace.45

Figure 2.16 Mouse (left) and Eye (right) movement traces relative to the erroneous target move on Caught (top row) and Uncaught (middle row) trials, and relative to a typical non-target move during a correct trial (Standard move; bottom row). Traces are plotted for the period prior to the movement (1), during the movement (2), and following the movement (3). Numbered circular markers indicate the beginning time points for each trace. The filled triangles on the eye-movement panels (right side) indicates the location of the response box.47

Figure 2.17 Average time spent looking at the target (ms) during the period preceding target movement (and following the previous movement). Plotted for the final, trial-terminating target move on Correct trials, for the first (erroneous) target move on Caught and Uncaught error trials, and for a typical non-target move on a correct trial (Standard). Error bars depict one standard error of the mean.49

Figure 2.18 Probability that the target template (co-extensive in space with the response box) was being inspected at times surrounding movement of the target (midpoint of the movement aligned to time zero). The sole target move was used for Correct trials (hashed line), while the first target move was used for Caught errors (thin black line) and Uncaught errors (thick grey line). Values were computed for the 5 seconds preceding and following the move. Correct trials (hashed) terminate following the target move, and so do not contribute data to the post-move period. Error bars depict one standard error of the mean.52

Figure 2.19 Proportion of trials in Experiment 5 having Caught errors (solid line) and Uncaught errors (dashed line), plotted across Set Size. Error bars depict one standard error of the mean.56

Figure 2.20 Move latencies (A) and durations (B) preceding, during, and following an Uncaught error. Lags refer to moves within a given error trial. Error bars depict one standard error of the mean.58

Figure 2.21 Response Times (seconds) for Experiment 6, plotted for each Instruction condition (Slow, None, Fast), across interaction methods (Mouse, Touch) and Set Size (12, 24). Error bars depict one standard error of the mean.64

Figure 2.22 Number of moves per trial for Experiment 6, plotted for each Instruction condition (Slow, None, Fast), across interaction methods (Mouse, Touch) and Set Size (12, 24). Error bars depict one standard error of the mean.65

Figure 2.23 Percent error for Experiment 6, with rates of Caught and Uncaught errors plotted separately. Error rates are plotted for each Instruction condition (Slow, None, Fast), across interaction methods (Mouse, Touch) and Set Size (12, 24). Error bars depict one standard error of the mean.....	68
Figure 2.24 Example display from the Forced Deposit condition in Experiment 7. When an item was selected, a red dot (white in the figure) would appear in a random unoccupied location in the grid at the top of the display. Participants were required to place the selected item in that position; otherwise the item would return to the position it had prior to being selected. The target item could also be moved directly to the response box.	71
Figure 2.25 (A) Response Times (seconds) and (B) Number of moves per trial for Experiment 7, plotted for Normal and Forced Deposit condition. Error bars depict one standard error of the mean. * $p < .001$	74
Figure 2.26 Caught and Uncaught error rates in Experiment 7, plotted for Normal and Forced Deposit conditions. Error bars depict one standard error of the mean.....	75

1. Introduction

The natural environment for human behaviour comprises enormous numbers of objects distributed across broad regions of space. Consequently, search can be seen as a necessary and central component of human behaviour, enabling us to locate and bring together the tools and resources required for a task, be they material, informational, or social. Search guides the deployment of limited receptive fields and attentional resources, selecting which aspects of the environment should be considered at each moment until the target is detected. With generality then, search can be described as an iterative *guess-and-check* process, with considerable variability in how the guessing is informed (e.g., by salience, memory, or prediction), and in how the checks are carried out (e.g., by covert attentional shifts, eye movements, or positional/postural changes in space). This characterization can be further understood as a specific instance of Neisser's 'perceptual cycle' (Neisser, 1976; Figure 1.1), such that an internal model generates a guess about the target location, which directs exploratory behaviours to sample the environment in order to evaluate the prediction. The results of this sample may then be used to update the model.

The existing search literature has studied a range of components in this model, but has predominantly focused on a particular subset. In Figure 1.2, each component of the perceptual cycle in Figure 1.1 has been subdivided to illustrate the range of sub-processes that may be considered, so that both the world itself and the exploratory processes engaged in search may be examined at multiple nested scales (i.e., with body position constraining head movements, head position constraining eye-movements, etc.), and the internal model may use a variety of different sources of information (e.g., stimulus characteristics, memory, prediction). Many of the earliest and best-understood characteristics of search have been investigated in the context of within-visual field attentional shifts (i.e., covert attention; Carrasco & McElree, 2001; Hunt & Kingstone, 2003; Posner, 1980), guided by salience- and feature-based target predictions (e.g., Duncan & Humphreys, 1989;

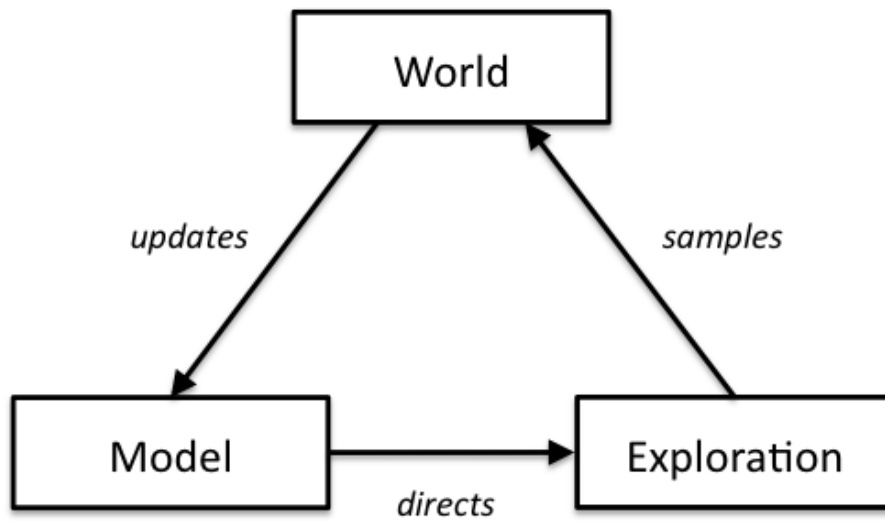


Figure 1.1 Neisser's Perceptual Cycle. Adapted from Neisser (1976).

Triesman & Gelade, 1980; Wolfe, 1994a, 2007). At this level of analysis, illustrated in Figure 1.2 as the Attention-samples-Visual Field subcomponent of the Exploration-samples-World arc, investigation has focused on evaluating how features of the visual array interact with the target representation to determine search performance, as measured by response times, hit rates and false alarms, and time-per-item slopes ('search efficiency').

Extensions to this original core of research exist for all three components of the cycle (often in combination), evaluating further aspects of the internal model, the nature of the search environment, and the exploratory behaviours. For instance, in addition to strictly feature-based models, considerable research has evaluated the influence of memory across various temporal scales (for an overview, see Shore & Klein, 2000), including (1) perceptual learning – i.e., learning across many trials (e.g., Brockmole, Castelano, & Henderson, 2006; Chun & Jiang, 1998, 1999; Endo & Takeda, 2005; Jiang & Leung, 2005; Jiang & Song, 2005; Leonard, Rettenbach, Nase, & Sireteanu, 2002; Olson & Chun, 2002; Sireteanu & Rettenbach, 1995), (2) within-trial memory for inspected locations (e.g., Dickinson & Zelinsky, 2007; Gilchrist, & Harvey, 2000; Horowitz & Wolfe, 1998, 2003; Körner, & Gilchrist, 2007; Kristjánsson, 2000; McCarley, Wang, Kramer, Irwin, & Peterson, 2003; Peterson, Beck, & Vomela, 2007; Peterson, Kramer, Wang, Irwin, & McCarley, 2001), (3) general trial-to-trial priming and inhibition (e.g., Goolsby & Suzuki, 2001; Hillstrom, 2000; Horowitz, 1995; Kumada & Humphreys, 2002; Maljkovic & Nakayama, 1994, 1996, 2000; McPeck, Maljkovic, Nakayama, 1999), and (4) trial-to-trial memory for specific items (e.g., Howard, Pharaon, Körner, Smith, & Gilchrist, 2011; Kunar, Flusberg, & Wolfe, 2008; Oliva, Wolfe, & Arsenio, 2004; Solman & Smilek, 2010, 2012; Vö & Wolfe, 2012; Williams, Henderson, & Zacks, 2005; Wolfe, Klempen, & Dahlen, 2000). Similarly, a great deal of work has investigated the role of prior experience and consequent expectancies for search in meaningful scenes (e.g., Biederman,

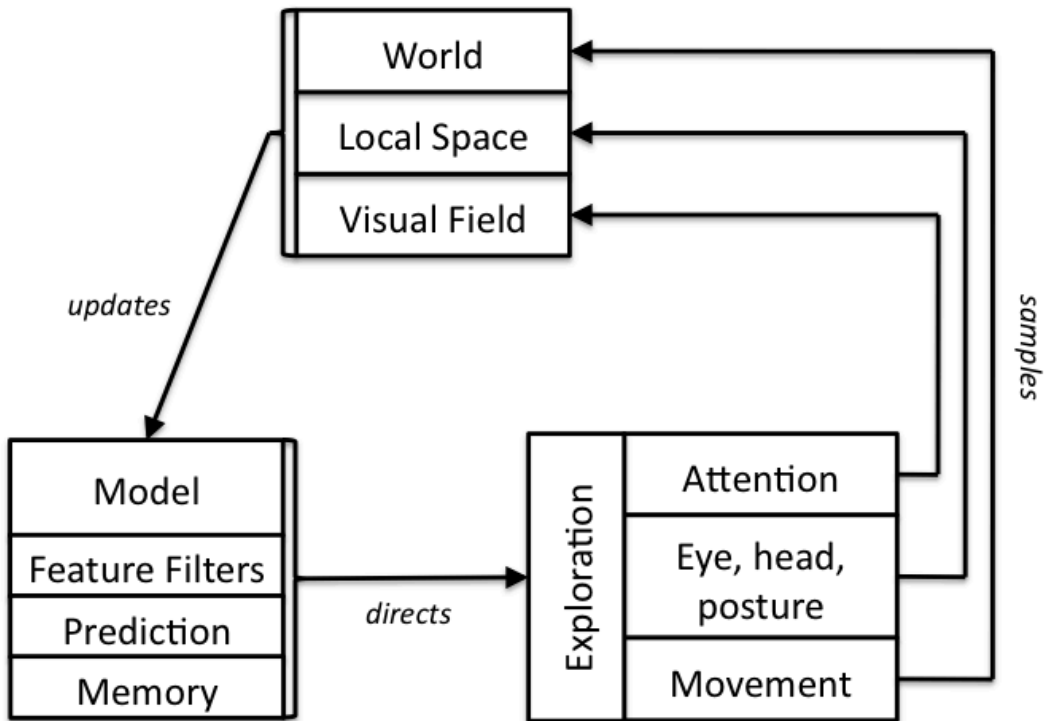


Figure 1.2 Expanded Perceptual Cycle as applied to search behaviour.

Mezzanotte, & Rabinowitz, 1982; De Graef, Christiaens, & d'Ydewalle, 1990; Eckstein, Drescher, & Shimozaki, 2006; Hollingworth & Henderson, 1998; Neider & Zelinsky, 2006; Torralba, Oliva, Castelhana, & Henderson, 2006).

Several lines of research, many overlapping with those discussed above, have also investigated how search can be influenced by the characteristics of the search environment. Whereas the classical visual search paradigm (i.e., Triesman & Gelade, 1980; designed to investigate the role of visual features in guiding attention), used randomly arranged and mostly semantically-meaningless stimuli, more recent work has attempted to generalize these findings to more ecological settings. Researchers have evaluated search in (1) displays with probabilistic item distributions (e.g., Geng & Behrmann, 2005; Lewicki, Czyzewska, & Hoffman, 1987; Miller, 1988; Smith, Hood, & Gilchrist, 2010; Williams, Pollatsek, Cave, & Stroud, 2009), (2) displays with repeated, or slowly varying item configurations (e.g., Chun & Jiang, 1998; Solman & Smilek, 2010; Wolfe, et al., 2000), (3) displays with complex moving and visually-changing items (Kunar and Watson, 2011), (4) naturalistic scenes and images (e.g., Brockmole et al., 2006; Eckstein, et al., 2006; Evans et al., 2011; Torralba, et al., 2006; Van Wert, Horowitz, & Wolfe, 2009; Wolfe, 1994b; Wolfe, Alvarez, Rosenholtz, Kuzmova, & Sherman, 2011; Wolfe, et al., 2007), and (5) large-scale search environments (e.g., Smith, Hood, & Gilchrist, 2008, 2010; Smith, Wallace, Hood, Gilchrist, 2009; Solman, Cheyne, & Smilek, In Press).

Finally, and most germane to the current work, studies of search have increasingly moved from covert attentional shifts within the visual field to overt exploratory behaviours that can alter the position (and thereby the contents) of the visual field. The bulk of this effort has made use of eye-movement recordings to examine how overt attention is deployed, and how overt and covert attention interact in guiding search (e.g., Acks, Zelinsky, & Sprott, 2002; Findlay & Gilchrist, 2003; Gilchrist & Harvey, 2000; Henderson, Brockmole, Castelhana, & Mack, 2007; Hooge & Erkelens, 1999; Howard et al., 2011; Itti & Koch, 2000; Motter & Holsapple, 2007; Najemnik & Geisler, 2005; Rao,

Zelinsky, Hayhoe, & Ballard, 2002; Solman, Cheyne, & Smilek, 2011; Yarbus, 1967; Zelinsky, Rao, Hayhoe, & Ballard, 1997). Scales of exploratory behaviours beyond eye-movements have only rarely been evaluated, even in the broader context of visual attention in general, with a small body of work examining head movements (primarily in applied settings; e.g., Barnes, 1979; Robinson, Koth, & Ringenbach, 1976; Summala, Pasanen, Räsänen, & Sievänen, 1996), mouse-mediated exploration / simulated embodiment (e.g., Smilek, Frischen, Reynolds, Gerritson, & Easwood, 2007; Solman, Cheyne, & Smilek, In Press), and fully-embodied search contexts (i.e., involving movement of the entire body in space: Smith, et al., 2008, 2009, 2010; or in virtual reality: Thomas et al., 2006).

These trends will no doubt continue, improving our models of search, and expanding the scope of situations to which these models can be applied. However, there is a further, qualitatively separable component of exploratory behaviour that has not yet been addressed in the context of search. In particular, exploration in naturalistic settings involves not only ‘receptive’ exploration (i.e., changes to the position of receptors and receptive fields with respect to the environment), but also ‘active’ exploration – where the configuration of the environment itself is manipulated and altered to facilitate search, illustrated in Figure 1.3 as a distinct class of exploratory behaviour. Active exploration is engaged when we open drawers and containers, leaf through stacks of papers, and rummage through bags, to give a few examples. Indeed, in many naturalistic settings, active exploration is *necessary* to successfully complete search – as in the case where a target is concealed, or contained. Consequently, failing to study active exploration limits our understanding of search in two ways – both in terms of how the exploratory process unfolds, and in terms of the range of search environments it is possible to study.

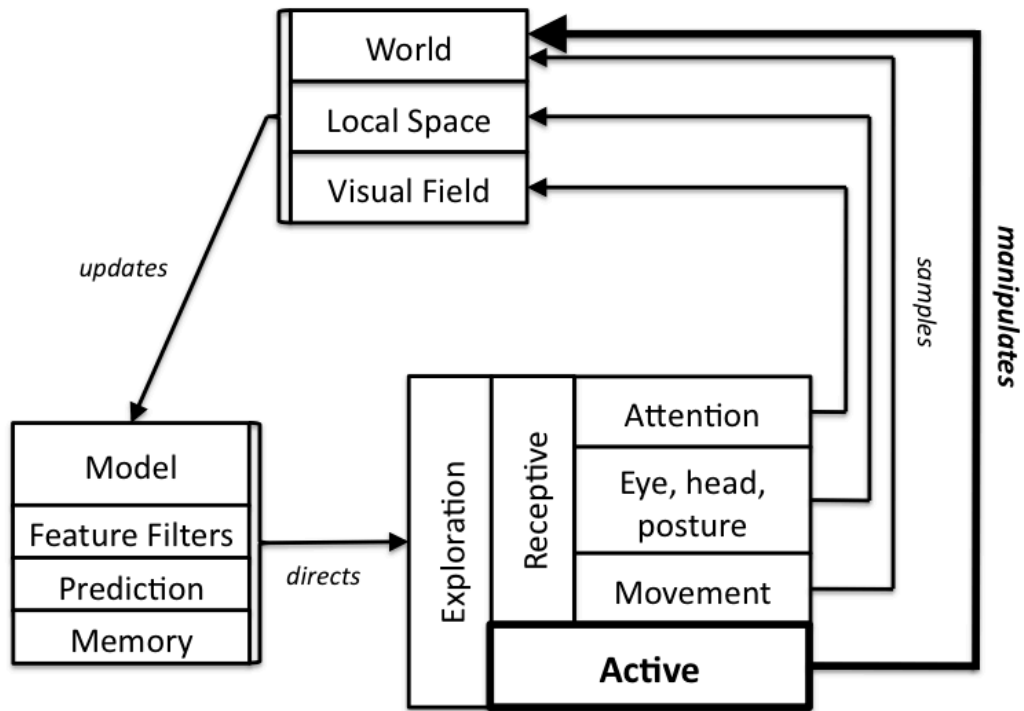


Figure 1.3 Expanded Perceptual Cycle for search, highlighting the novel component of active exploration.

This gap in our understanding may be particularly consequential given the centrality of action to the study of psychology and human behaviour (e.g., Cisek, 2007; Cisek & Kalaska, 2010; Gottlieb, 2007; Rosenbaum, 2005), and the close interactions and overlaps between motor and sensory systems (e.g., Ambrosini, Sinigaglia, & Costantini, 2012; Berman & Colby, 2009; Gordon, et al., 2011; Hannus, Cornelissen, Lindemann, & Bekkering, 2005; Hatsopoulos & Suminski, 2011; Nii, Uematsu, Lesser, & Gordon, 1996). Further, in addition to the theoretical importance of motor behaviour, there is a growing body of research drawing critical insights about cognition through use of continuous motor responses as a *measure* (for review, see Freeman, Dale, & Farmer, 2011). For these reasons, studies of search must be expanded to incorporate active exploratory behaviours. This thesis provides an initial effort to address this need.

2.The Experiments

The present research was motivated by the absence in the existing search literature of studies examining active exploration in search. A novel search paradigm, the ‘Unpacking Task,’ was developed – introducing a search context that allowed participants to physically interact with the search items. Participants performed a computer-based search task, in which a heap of overlapping search items was presented on the screen and subjects were instructed to use the mouse to ‘unpack’ the heap in order to locate a target item. This task simulated everyday search behaviors, such as looking for an object in a full drawer or on a cluttered desk, contexts that require the searcher to move objects to find the target. While performing this task, it was observed that participants would often make a striking error in which the target item was actually selected, moved, and rejected without being recognized. Notably, this error occurred even though the target was present on every trial, and trials would terminate only when this target was successfully located.

In Experiments 1 and 2, we introduce this ‘unpacking error,’ and evaluate the effects of three traditional visual search manipulations on error prevalence: 1) set size, 2) item similarity, and 3) dual task conditions (concurrent memory load). We demonstrate a robust effect of item similarity, but minimal impacts of either set size or memory load on the prevalence of the error, and consequently argue that the error must have a perceptual root, but is unlikely to arise from a central resource limitation. In Experiment 3, we evaluate a perceptual-motor dissociation account, introducing a yoked-vision condition wherein an item’s identity is available only while it is being acted upon, forcing a tighter coupling between perception and action. Remarkably, we find that the rate of consequential errors is unaffected by this manipulation. Tellingly, we also find that the severity of an error, as measured by its consequences, is reduced in the yoked-vision condition. Consistent with the effects of item similarity, this finding suggests that items not yet fully processed may suffer from

interference by other items in the display. In Experiment 4, we evaluate the error more closely by measuring both eye-movements and mouse-movements during the task. Here we rule out the trivial account that participants simply fail to look at the target before moving it, and provide additional detail about the temporal and spatial characteristics of the error. In Experiment 5, we assess individual move characteristics preceding and following an error, and provide evidence for unconscious recognition of the error as indexed by robust post-undetected-error slowing. In Experiment 6, we evaluate whether the perceptuomotor incoordination hypothesized to cause the error may reflect task specific idiosyncrasies and not a naturalistic outcome. In particular, we compare: (1) use of the mouse to use of a touch screen, and (2) three different participant instructions emphasizing speed to varying degrees. We find that the error is increased when using the more naturalistic interface (the touch screen), and that instructional manipulations have little influence on participant behaviour – improving our confidence in the ecological validity of the findings. In Experiment 7, we directly manipulate movement speed by introducing a forced deposit condition, and demonstrate that the error is significantly attenuated when participants are forced to plan their movements more carefully. Finally, we provide a meta-analysis of the results across all comparable conditions to evaluate the possibility of a Set Size effect on the error rate. We find that, with sufficient power, a small effect of Set Size on error rates is detectable.

In summary, we suggest that the unpacking error reflects a fundamental dissociation between perception and action during manually-assisted search. In particular, despite the obvious requirement that potential targets be inspected before being selected or discarded, it appears that the motor system is only loosely constrained by this perceptual requirement and need not wait for feedback signaling complete perceptual inspection and decision. Such motor haste likely speeds motor-assisted search overall, but means that the perceptual system is often left to play catch-up with the consequences of these movements, and so item identification may be left incomplete. When this happens with target

items, the unpacking error occurs as the target is selected, moved, and rejected prior to full identification. These conclusions, and their implications for search are expanded in the General Discussion.

2.1 Experiment 1

In Experiment 1, we introduce the Unpacking Task – a novel search task in which participants use the mouse to search through a virtual heap of items presented as square cards on a computer display. During this task, we find that participants sometimes select and move the target item without recognizing it as the target – a phenomenon we term the ‘unpacking error’. We manipulate Set Size and inter-item similarity, and show that the unpacking error is more prevalent in conditions where items are similar to each other (and consequently difficult to discriminate), but that the error rate does not appear to be influenced by Set Size.

Methods

Subjects. Sixteen undergraduate students (15 female, 1 male) from the University of Waterloo participated for course credit. All participants reported normal or corrected-to-normal visual acuity, and normal color vision.

Search Items. Each item was displayed on a square gray virtual ‘card’ subtending 3 degrees of visual angle (d.v.a.). Items on a given trial were selected from one of two item sets. The Dissimilar item set had 32 possible items, comprising the full cross of four shapes (circle, square, triangle, star) and eight colors (all of the possible 3-bit RGB colours). The Similar set had 24 possible items, each comprising a white bounding square and a unique pattern of horizontal and vertical white lines (Figure 2.2).

Displays. Examples of a Dissimilar and Similar search display are shown in panels A and B of Figure 2.1, respectively. Each search display consisted of a gray screen with a heap of overlapping

items centered on the screen, and a target template displayed in a green box on the right side of the screen. The target box subtended 6 d.v.a. and was centered on a point one third the width of the screen from the right side and centered vertically. The stack of items consisted of either 12 or 24 of the items from either the Dissimilar or the Similar set. Initial item positions were generated randomly within a bounding box centered on the screen. To vary the overall degree of overlap, this bounding box had a total area of either 0.3 (high overlap), 0.8 (medium overlap), or 1.3 (low overlap) times the total area that would be required to display all of the items without overlap. For set size 12 these boxes were 5.6 d.v.a., 9.2 d.v.a., and 11.7 d.v.a., respectively. For set size 24 these boxes were 7.9 d.v.a., 13.0 d.v.a., and 16.5 d.v.a., respectively.

Procedure. Each trial began with the appearance of the search display. Participants were instructed to find the target as quickly as possible, the template for which was shown in the green box on the right side of the screen (Figure 2.1). They could use the mouse to move items anywhere on the screen to uncover occluded items. The trial was terminated when participants found the target and dragged it onto the green box containing the target template. The next search trial commenced after a 250 ms delay. Three factors were intermixed over the course of 240 trials: Set Size (12, 24), Item Type (Dissimilar, Similar), and overlap (High, Medium, Low; see *Displays* section). Participants performed 5 practice trials followed by 240 experimental trials. The initial configuration of the items, as well as the grab time, drop time, and drop coordinates of each moved item were recorded.

The experiment was created in MATLAB, using version 3 of the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), and run on an Apple mini, with OS X 10.6.4 and a 2.4GHz Intel Core 2 Duo processor. The stimulus displays were presented on a 19" ViewSonic VA1912wb monitor at a resolution of 1440 by 900 at a distance of 55 cm.

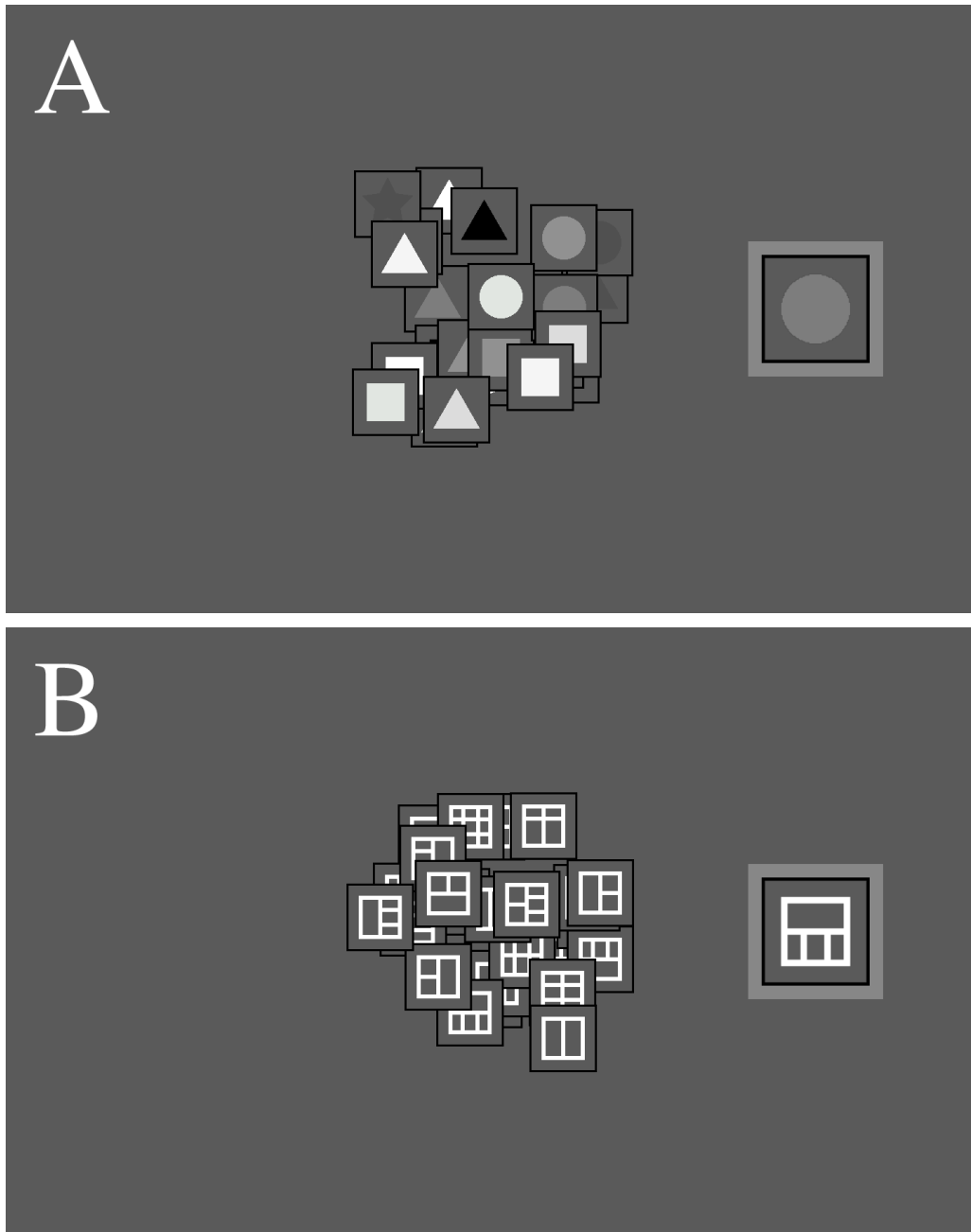


Figure 2.1 Sample displays for the Dissimilar item set (A) and Similar item set (B). Participants were instructed to locate the target item, displayed in the green box on the right, and to drag it onto the green target box.

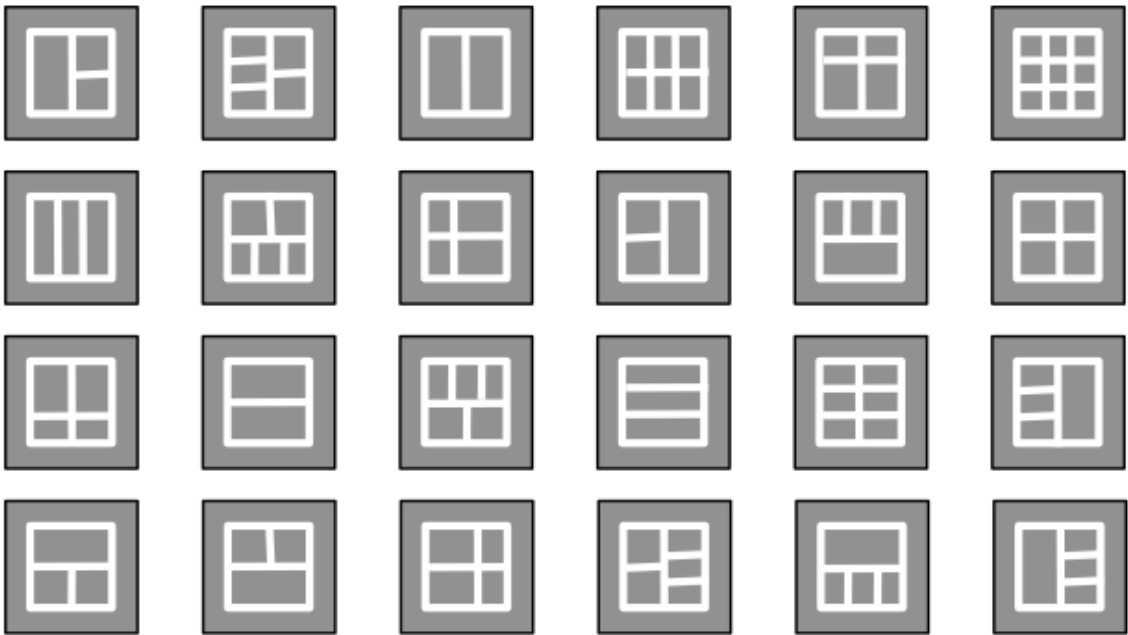


Figure 2.2 Search items composing the Similar stimulus set.

Results

Response Times. Response Times (RTs) were measured from trial onset to release of the target item inside the response box, and were analyzed for all trials. The values of this measure were highly skewed, and so were adjusted using a log transform. The values plotted and analyzed are based on the anti-logs of the mean log RTs for each subject. Overall RTs are plotted across Set Size in Figure 2.3, for both Similar and Dissimilar items. Analyzing RTs with a Type (Dissimilar, Similar) by Set Size (12, 24) ANOVA, we found all effects to be highly significant (all $F_s > 193$, $p_s < .001$). In particular, search was both faster and more efficient (shallower time/item slopes; Type by Set Size interaction) for Dissimilar than for Similar items.

Unpacking Errors. Unpacking error trials were defined as trials on which the target was moved (i.e., selected by depression of the mouse button, and dropped by release of the mouse button) without terminating search. These trials were further subdivided into ‘Caught’ and ‘Uncaught’ errors. Caught errors were those trials where the target item was moved twice in succession, i.e. once in error, with the next move terminating the trial. Uncaught errors occurred on those trials where at least one non-target item was moved between the first (erroneous) target move, and the final (trial-terminating) target move. Error rates for Caught and Uncaught errors are plotted across set size for Similar and Dissimilar items in Figure 2.4. These data were analyzed with an Error Type (Caught, Uncaught) by Type (Dissimilar, Similar) by Set Size (12, 24) repeated measures ANOVA. Overall, participants made significantly more errors for the Similar item set than for the Dissimilar set, $F(1, 15) = 20.69$, $MSE = .003$, $p < .001$. In addition, item set interacted with error type, $F(1, 15) = 15.70$, $MSE = .001$, $p < .005$. For Similar items, Caught and Uncaught errors were equally prevalent ($F = 1.04$, $p = .325$), whereas for Dissimilar items, Uncaught errors were significantly less likely than Caught errors, $F(1,15) = 28.9$, $MSE = .001$, $p < .001$. No other effects reached significance (largest $F = 2.9$, $p = .111$). Finally, despite a strong effect of Set Size on response times, there was no measurable effect on

error rates ($F = 2.8$, $p = .115$). In summary, these results suggest a perceptual basis for the unpacking error, and provide a preliminary indication that the error is unlikely to arise from a central resource limitation, or from a similar load-dependent mechanism.

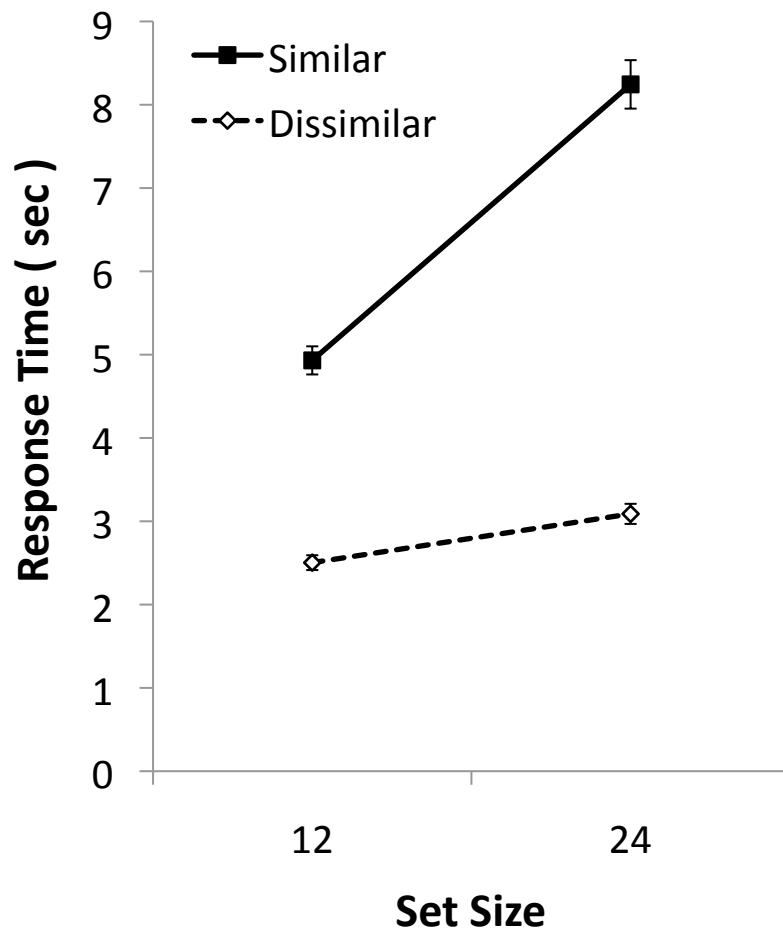


Figure 2.3 Response Times (seconds) for Experiment 1, plotted across Set Size for Similar items (solid line) and Dissimilar items (dashed line). Error bars depict one standard error of the mean.

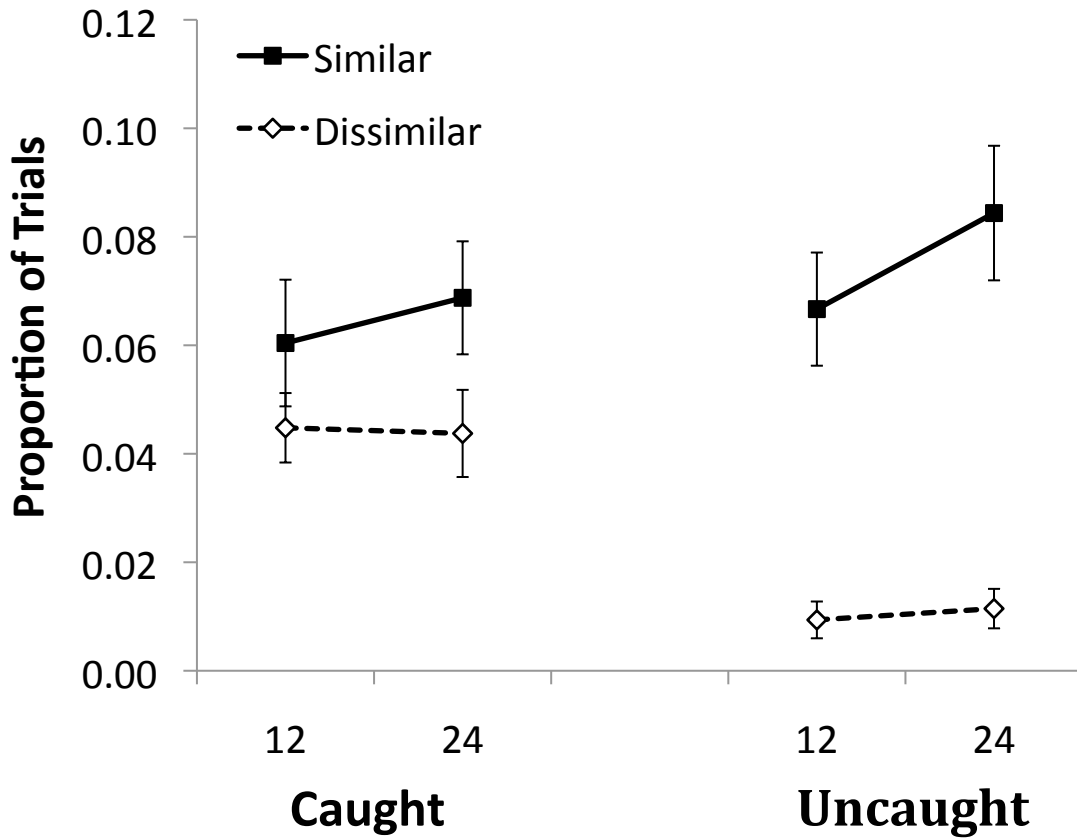


Figure 2.4 Proportion of trials having Caught errors (trials where the target was moved twice in succession, with the second move being to the target box) and Uncaught errors (trials where the target was moved at least twice, with at least one intervening non-target move) in Experiment 1. Values are plotted across Set Size for Similar items (solid line) and Dissimilar items (dashed line). Error bars depict one standard error of the mean.

2.2 Experiment 2

One possible explanation for the unpacking error is that participants may simply forget the identity of the target while searching. By this account, the error would occur when participants moved the target item in the period between forgetting its identity and re-inspecting the target template. This explanation is weakened by the absence of a set size effect on error prevalence, as we would expect more episodes of forgetting as trial length increases at higher set sizes. Nonetheless, the memory failure account merits a more direct evaluation. In Experiment 2 the unpacking task was performed both alone and with the addition of a concurrent memory load, a manipulation known to impair visual search performance (e.g. Woodman, Vogel, & Luck, 2001). If the unpacking error occurs because participants forget the target identity, then error prevalence should increase as memory load increases.

Methods

Subjects. Twenty-eight undergraduate students (19 female, 9 male) from the University of Waterloo participated for course credit. All participants reported normal or corrected-to-normal visual acuity, and normal color vision.

Displays. Search displays were identical to those in Experiment 1, but using only the Similar item set. Each memory load trial also included two memory displays (sample and test). Memory sample displays replicated those used in Woodman, Vogel, & Luck (2001), consisting of four small colored squares presented centrally. Memory test displays were identical to the sample on half of the trials, and different for the other half. When non-matching, the memory test displays differed from the sample by changing the color of one random square.

Procedure. The procedure used in Experiment 2 was similar to that of Experiment 1, with the exception of an added concurrent memory task on half of the trials. On Load trials, a memory sample was displayed for 500 ms, followed by a 500 ms fixation display, then onset of the search display,

which was terminated when the target was moved to and deposited on the green target template box (recall Figure 2.2). After search was terminated, a blank screen was displayed for 500 ms, followed by a memory test display presented for 2,000 ms. Participants had to report whether the memory sample and test displays were the same or different on that trial. Responses were given after the presentation of the memory test display during which time the screen indicated the response options ('SAME': 'm' key vs. 'DIFFERENT': 'z' key). Once the response to the memory test display was given, the display with the response options was terminated and a blank screen appeared for 500 ms followed by onset of the next trial. On No Load trials, each trial was preceded by a 1,000 ms fixation display. We recorded memory task accuracy, as well as the initial configuration of the items, and the grab time, drop time, and drop coordinates of each move during search.

Memory Load was blocked, with 120 trials of search alone, and 120 trials of search under Load. The order of these conditions was counterbalanced across participants. Each block of 120 trials consisted of 60 trials at Set Size 12, and 60 trials at Set Size 24, randomly intermixed. During Load trials, the test matched the sample on 50% of the trials. The ratio of the bounding area to total item area was drawn randomly from the range [0.5, 1.0] on each trial. All trials used the Similar item set only. Participants were given 5 practice trials followed by 240 experimental trials.

Results

Memory Task Performance. Participants responded correctly on the memory task on 81.4% and 80.2% of trials for Set Size 12 and 24, respectively. These values were not significantly different ($F < 1, p > .48$).

Response Times. As in Experiment 1, Response Times were highly skewed, and so the presented values are the anti-logs of the mean log RTs. Overall Response Times (excluding load trials with memory errors) are plotted in Figure 2.5, and were tested with a Memory Load (Load, No Load) by Set Size (12, 24) ANOVA. The analysis showed a robust effect of Set Size, $F(1, 27) = 390.5$, $MSE =$

0.68, $p < .001$, and also, critically, a strong effect of Memory load, $F(1, 27) = 13.1$, $MSE = 1.23$, $p < .005$. The interaction was not significant (no change in efficiency; $F < 1$, $p > .5$).

Unpacking Errors. The rates of Caught and Uncaught unpacking errors (again excluding load trials with memory errors) are plotted in Figure 2.6. The data were analyzed with an Error Type (Caught, Uncaught) by Memory Load (Load, No Load) by Set Size (12, 24) ANOVA. No effects reached significance (largest $F = 2.6$, $p = .122$). As in Experiment 1, we note that despite robust effects of both Set Size and Memory Load on overall RTs, neither of these effects had measurable consequences on the rate of the unpacking error. These results again speak against an account of the error requiring a central resource limitation. In addition, the lack of a memory load effect on the prevalence of the unpacking error also suggests that the error is not the result of participants simply forgetting the target during the course of the trial.

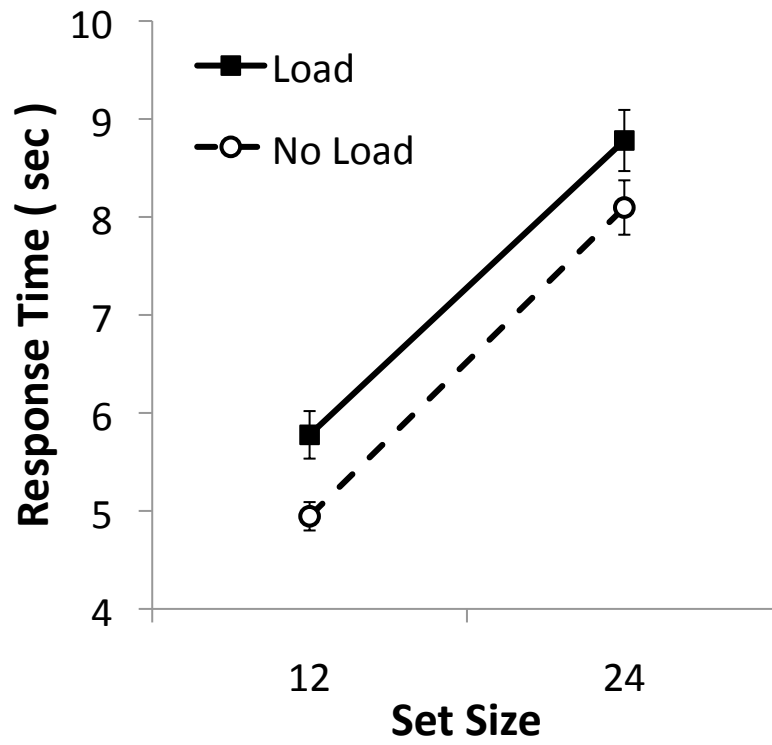


Figure 2.5 Response Times (seconds) for Experiment 2, plotted across Set Size for search under Load (solid line) and No Load (dashed line) conditions. Error bars depict one standard error of the mean.

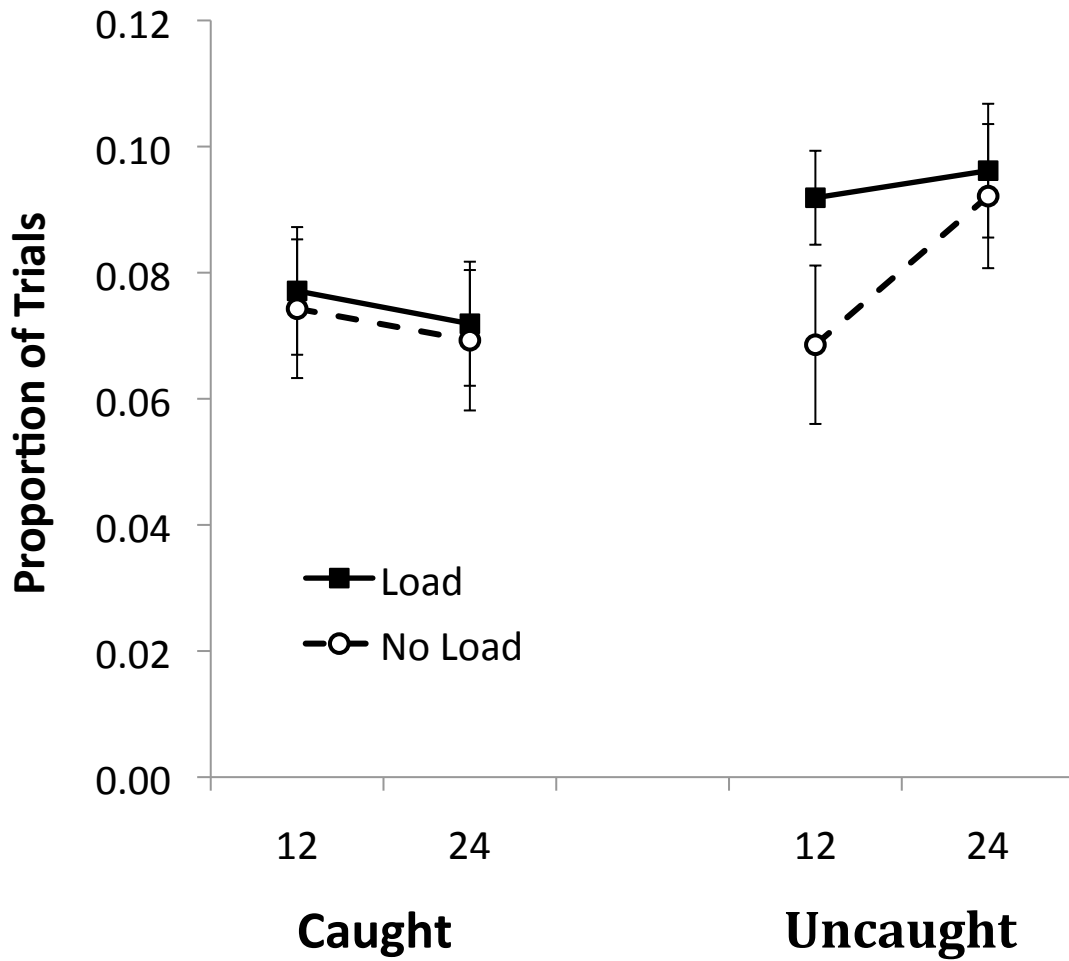


Figure 2.6 Proportion of trials having Caught errors and Uncaught errors in Experiment 2. Values are plotted across Set Size for search under Load (solid line) and No Load (dashed line) conditions. Error bars depict one standard error of the mean.

2.3 Experiment 3

In Experiments 1 and 2, we found that participants often interact with the target item but fail to recognize it during the unpacking task. Notably, the prevalence of the unpacking error seems to be influenced only by the perceptual characteristics of the items, and not by either set size or memory load manipulations, discounting an explanation relying on central resource limitations. An alternative possibility is that the unpacking error reflects a dissociation between the motor processes engaged in moving and uncovering items in the display, and the perceptual processes engaged in analyzing those items thereby made available for inspection. An intuitive expectation for manually-assisted search would be that items should be identified prior to manipulation – in order to determine whether the item should be rejected or submitted as the target. The existence of the unpacking error however, suggests that this intuitive sequence, ‘inspect, decide, act,’ is not necessarily followed. Instead, it may be that the motor system takes precedence (a ‘motor first’ strategy), or that the two systems operate in parallel, and are not necessarily bound to the same item.

In Experiment 3, we attempt to clarify these distinctions by forcing a tighter coupling between perceptual and motor processes. To this end, we introduce a yoked-vision condition, wherein the identity of an item is only visible while that item is being acted upon. This manipulation has two principle effects. First, we can explicitly assess the degree to which participants evaluate the identity of an item prior to moving it, as the item’s identity is only available upon selection. A second, indirect effect of this manipulation is to reduce the overall perceptual load of the display without changing the perceptual difficulty of processing an individual item.

Consequently, we can make the following predictions. A pure ‘inspect, decide, act’ strategy would result in moves characterized by a stationary component after depression of the mouse button, followed by a directed ballistic movement either to the response box for the target item, or to some other location on the screen for rejected item. In this case, error rates should either be unaffected, or

else should be reduced – as the yoked-vision condition ensures there is no competing perceptual information while an item is being inspected. In contrast, a ‘motor first’ strategy would result in moves characterized by an immediate ballistic movement, undifferentiated for target and non-target items. In this case, we would expect a marked increase in error rates, as the movement would likely often terminate prior to the completion of inspection, and in the case of correct responses we would expect evidence of in-flight correction in movement.

Methods

Participants. Twenty undergraduate students (14 female, 6 male) from the University of Waterloo participated for course credit. All participants reported normal or corrected-to-normal visual acuity, and normal color vision.

Displays. Search displays were identical to those used in previous experiments, again using only the Similar item set. Full-vision trials were identical to previous experiments (Figure 2.2, panel B), whereas on Yoked-Vision trials items were displayed as undifferentiated solid gray ‘cards’ until they were selected. While selected (from mouse depression to mouse release), an individual item’s identity was visible (Figure 2.7).

Procedure. Each trial began with the appearance of the search display. Participants were instructed to find the target as quickly as possible, the template for which was shown in the green box on the right side of the screen (recall Figures 2.2, 2.7). They could use the mouse to move items anywhere on the screen to uncover occluded items. The trial was terminated when participants found the target and dragged it onto the green box containing the target template. The next search trial commenced after a 250 ms delay. On Full-vision trials, the identity of the item on each virtual card was continuously visible throughout the trial (Figure 2.2, panel B). On Yoked-vision trials, item identities were displayed only for selected items, appearing at the onset of item selection (depression of the

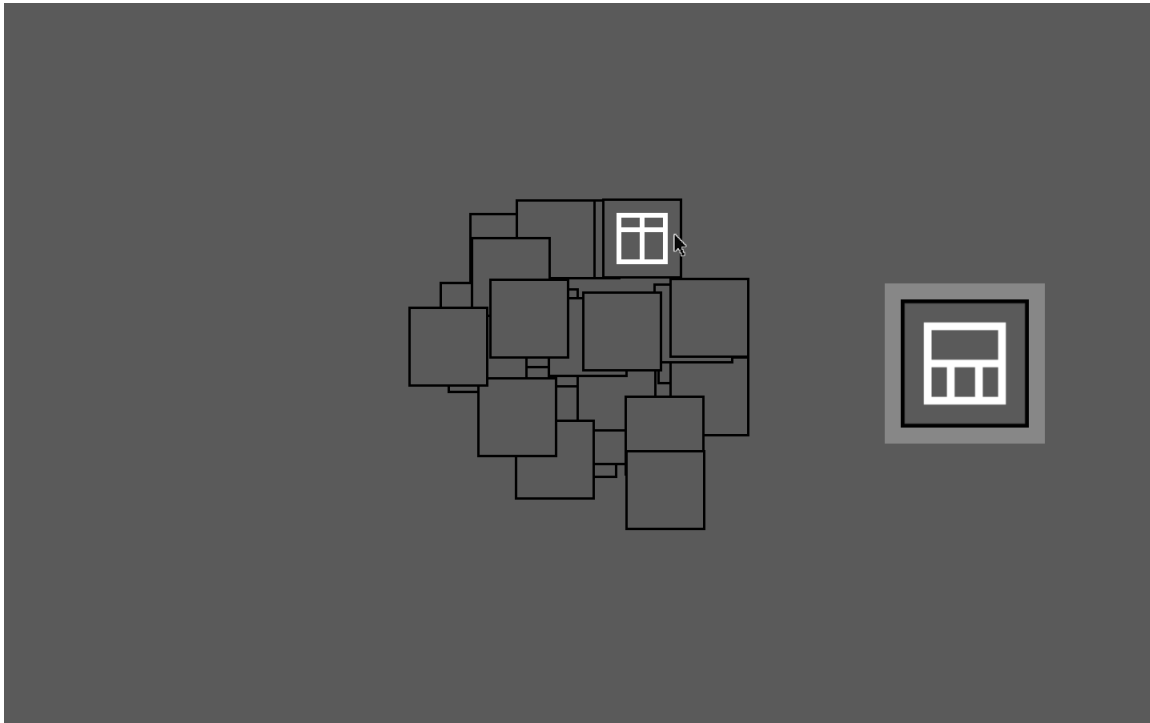


Figure 2.7 Example display from the Yoked-vision condition in Experiment 3. Each item was displayed only as a blank grey card unless it had been selected. The identity of a selected card was visible only while the mouse button was depressed. The target template was always visible.

mouse button), and disappearing on release of the item (release of the mouse button). When unselected, all items appeared as identical featureless grey cards (Figure 2.7).

Participants completed 80 trials of Full-vision search and 80 trials of Yoked-vision search, blocked with order counterbalanced across participants, with an equal number of each Set Size (12, 24) randomly intermixed in each block. Participants performed 3 practice trials of each type prior to beginning the experimental trials. The initial configuration of the items, as well as the grab time, drop time, and drop coordinates of each moved item were recorded. In addition, the state of the mouse was sampled throughout the experiment (see *Appendix A: Trace Computation*).

Apparatus. The experiment was created in MATLAB, using version 3 of the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), and run on an Apple mini, with OS X 10.6.4 and a 2.4GHz Intel Core 2 Duo processor. The stimulus displays were presented on a 19" ViewSonic VA1912wb monitor at a resolution of 1440 by 900 at a distance of 55 cm.

Results

Response Times. Response Times were taken as the time between onset of the search display, and release of the target item within the response box. Response times were again positively skewed, and hence log - anti-log transformations were again employed. The data (Figure 2.8) were analyzed with a Vision (Full, Yoked) by Set Size (12, 24) repeated measures ANOVA. Search was found to be faster for Full-vision than for Yoked-vision, $F(1, 19) = 102.6$, $MSE = 1.021$, $p < .001$, faster for the smaller set size, $F(1, 19) = 332.8$, $MSE = 0.998$, $p < .001$, and more efficient (i.e., shallower time/item slopes; Vision by Set Size interaction) for Full-vision than for Yoked-vision, $F(1, 19) = 5.9$, $MSE = 0.543$, $p < .05$.

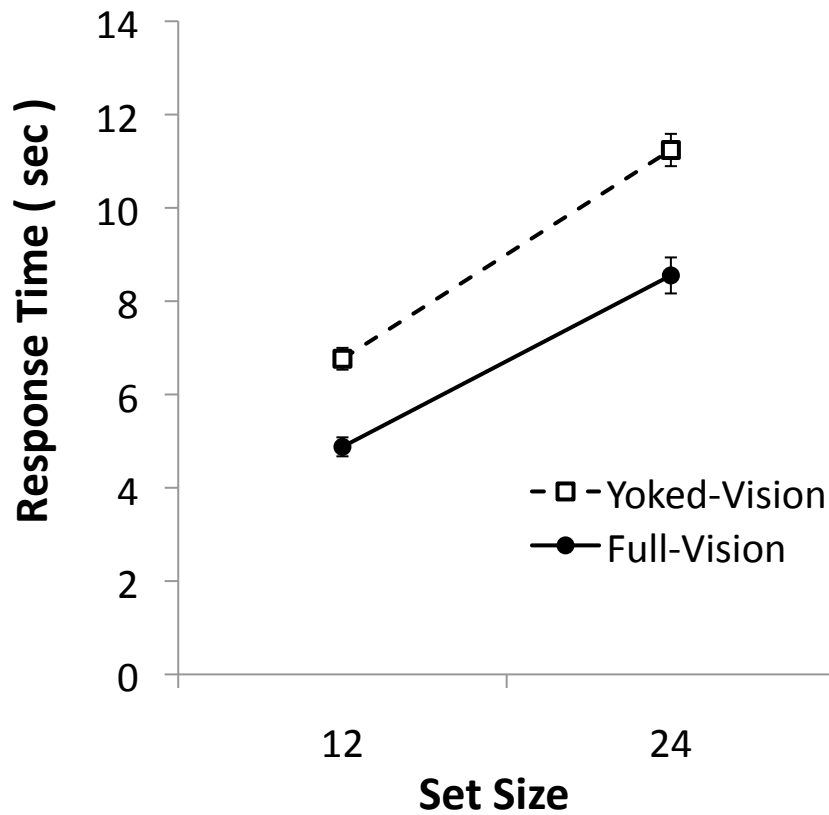


Figure 2.8 Response Times (seconds) for Experiment 3, plotted across Set Size for search under Yoked-vision (dashed line) Full-vision (solid line) conditions. Error bars depict one standard error of the mean.

Unpacking Errors. The rates of Caught and Uncaught unpacking errors are plotted in Figure 2.9 for both Vision conditions across Set Size, and were analyzed with an Error Type (Caught, Uncaught) by Vision (Full, Yoked) by Set Size repeated measures ANOVA. All three main effects were significant ($F_s > 4.6$, $p_s < .05$), but were qualified by interactions. In particular, we observed both a significant Vision by Set Size interaction, $F(1, 19) = 6.50$, $MSE = .002$, $p < .05$, and a significant Vision by Error Type interaction, $F(1, 19) = 107.4$, $MSE = .015$, $p < .001$. To clarify these interactions, we first conducted a separate Error Type by Set Size ANOVA for each Vision condition. A significant effect of Set Size was observed for Yoked-Vision, $F(1, 19) = 7.24$, $MSE = .005$, $p < .05$, but not for Full-Vision ($F < 1$). Similarly, a prominent effect of Error Type was observed for Yoked-Vision, $F(1, 19) = 84.8$, $MSE = .032$, $p < .001$, but not for Full-Vision ($F = 1.4$, $p = .245$). The interactions were not significant ($F_s < 1$). To further highlight the nature of the omnibus Vision by Error Type interaction, we performed an additional Vision by Set Size ANOVA for Caught and Uncaught errors separately, to evaluate the effect of Vision condition on each of the error types. As is clear from the figure, there were significantly more Caught errors under Yoked-Vision conditions, $F(1, 19) = 94.4$, $MSE = .031$, $p < .001$. The high rate of Caught errors under Yoked-Vision is a natural consequence of the definition of the error and of the manipulation – the first time a participant can see the identity of an item is during its first movement, and any instance where the target is dropped at the end of this first movement and then immediately retrieved is coded as a Caught error. Most critically, and strikingly, there was no measurable difference across Vision conditions in the rate of Uncaught errors ($F < 1$, $p > .5$).

Movement Traces. Mouse movements were recorded throughout performance of the task, enabling analysis of movement trajectories. Here we evaluate the first (erroneous) target move for both Caught and Uncaught error trials, and contrast these to the trial-terminating target move on Correct trials, and to a typical non-target move on Correct trials (Standard move). The movements were evaluated for

two primary purposes. First, we assessed the task-relevant spatial characteristics of the moves, by examining how much of the movement at each sample was directed towards the response box – as this is where the item should be placed for a correct target identification (measured by projection of the instantaneous movement vector onto the vector directed to the response box location; see *Appendix A* for full methodological details of trace computation). Second, we examine several more traditional temporal metrics of the movements: 1) total movement time, 2) peak speed, and 3) time to peak speed. All metrics are examined separately for each Vision condition.

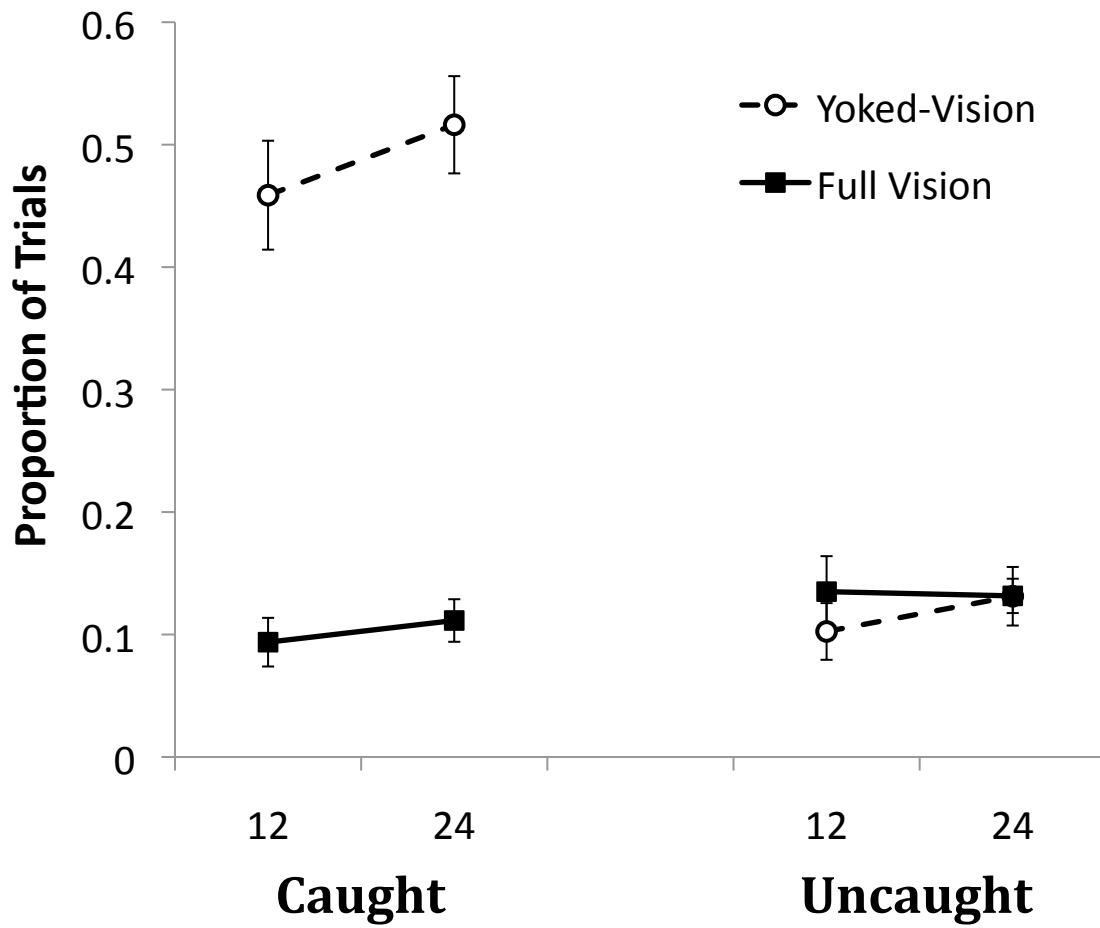


Figure 2.9 Proportion of trials having Caught errors and Uncaught errors in Experiment 3. Values are plotted across Set Size for search under Yoked-vision (dashed line) and Full-vision (solid line) conditions. Error bars depict one standard error of the mean.

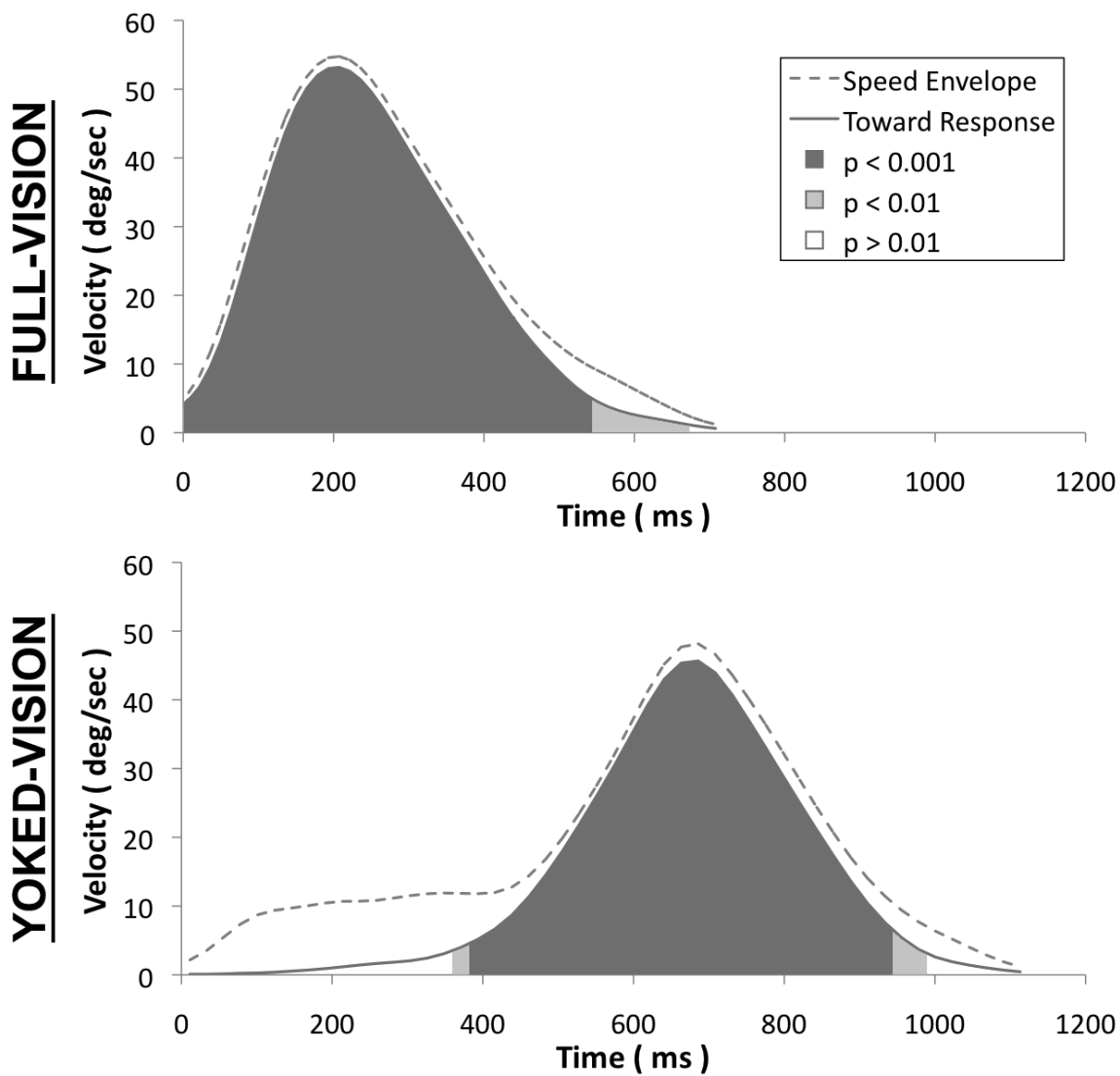


Figure 2.10 Characteristics of mouse movements for trial-terminating target moves on correct trials, plotted for Full-vision and Yoked-vision conditions. The dashed line indicates the total velocity of the movement (in degrees per second), while the solid line indicates the component of this movement in the direction of the response box. Positive values indicate movement toward the response box, and negative values indicate movement away from the response box. Shading represents the significance level for a t-test against zero.

We first examine the trial-terminating target move on Correct trials, plotted for Full-Vision and Yoked-Vision conditions in Figure 2.10. The grey hashed line indicates the overall, undirected, instantaneous speed. The solid line indicates the instantaneous component of the movement directed towards (positive deflection) or away from (negative deflection) the response box. This directed component was tested against zero at each sample. In the figure, the area under the curve is shaded to indicate significance. Dark shading indicates samples significantly different under a conservative Bonferroni correction ($\alpha = .001$), light shading indicates samples significantly different at a more liberal threshold ($\alpha = .01$), and non-shaded areas indicate samples not significantly different from zero at either alpha level.

Under Full-Vision conditions, the trial-terminating target move consists of a single, rapidly-executed movement towards the response box, taking approximately 715 ms, with a peak speed of $59.9^\circ/\text{s}^1$ at 207 ms. Comparing the undirected speed envelope to the component directed towards the response box, we can see that the overall movement is directed almost perfectly towards the response box.

A very different picture emerges under Yoked-vision conditions. Here, movement towards the response box is not initiated at the onset of target selection. Instead, for a period of roughly 350 ms, the item is moved in a direction orthogonal to the response box (positive speed envelope with component trace not different from zero), followed by a rapid movement towards the response box, signaling recognition of the target. Total movement time is approximately 1124 ms, with peak speed at 680 ms. Notably, subtracting recognition time, the remaining movement has a comparable duration and peak time to that observed under Full-Vision conditions. Likewise, the peak velocity of $58.3^\circ/\text{s}$ is not different from that under Full-Vision ($t(19) < 1, p > .5$). Critically, this pattern of movement is not

¹ The peak speed reported here is slightly different from that observed in the Figure because the peak occurred at differing time points for different subjects.

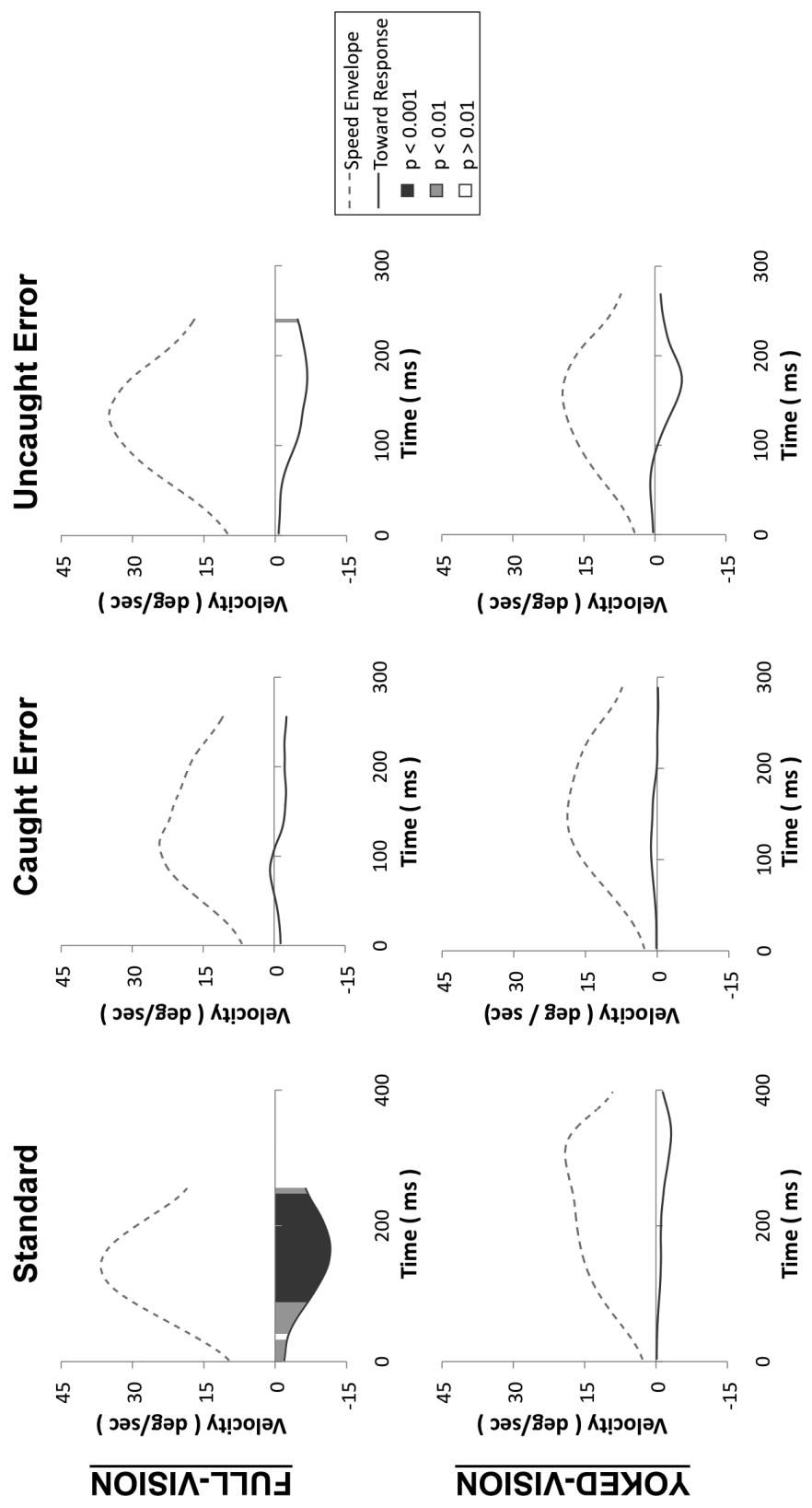
consistent with an ‘inspect, decide, act’ behavioral sequence, but instead with a mid-flight correction to an already initiated rejection.

We next evaluate the movement traces for the first (erroneous) target movement in both Caught and Uncaught errors, and compare this movement to a Standard non-target item movement. We plot these traces in Figure 2.11, for both Vision conditions and all three move types (Standard, Caught, Uncaught)². The most critical feature is clearly evident across all panels. Specifically, in all cases the move is directed either completely orthogonal to, or slightly in the opposite direction from the response box. In other words, on both Caught and Uncaught error trials, the first target move during the trial is qualitatively indistinguishable from a typical non-target move. This finding is particularly informative for Caught errors, as it rules out the trivial case of ‘undershoots’ – where participants perhaps intended to move the target item to the response box but accidentally dropped it too soon. Instead, it is clear that at no point during the move is there any component directed towards the response box.

A closer look at the detailed metrics does indicate some differentiation between these movement classes. First examining the Full-Vision case, we find that all three moves have similar total duration (Standard: 257 ms, Caught: 258 ms, Uncaught: 243 ms; no significant differences), and similar peak times (Standard: 141 ms, Caught: 118 ms, Uncaught: 131 ms; no significant differences), but that peak velocity is lower for Caught errors (26.9°/s) than for Standard moves (37.9°/s) or Uncaught errors (37.5°/s) ($t_s > 3.5$, $p_s < .005$), while peak velocity did not differ between Standard moves and Uncaught errors. For Yoked-Vision we find a different pattern of results. While peak velocities did

² We do not include the final, trial-terminating, target move in the figure or in the subsequent analyses, but we note here for the interested reader that these moves were qualitatively indiscriminable across error types and correct trials.

Figure 2.11 Characteristics of mouse movements for erroneous target moves on Caught and Uncaught error trials, and for a comparison non-target move on correct trials (Standard) plotted for Full-vision and Yoked-vision conditions. The dashed line indicates the total velocity of the movement (in degrees per second), while the solid line indicates the component of this movement in the direction of the response box. Positive values indicate movement toward the response box, and negative values indicate movement away from the response box. A value at zero indicates movement orthogonal to the direction of the response box. Shading represents the significance level for a t-test against zero.



not differ (Standard: 26.2°/s, Caught: 23.3°/s, Uncaught: 25.9°/s), total durations for both Caught (291 ms) and Uncaught (271 ms) errors were significantly shorter than for Standard moves (401 ms) ($t_s > 6.2$, $p_s < .001$). Caught and Uncaught errors did not differ from each other on this measure. Likewise, peak times for both Caught (168 ms) and Uncaught (157 ms) errors were shorter than for Standard moves (242 ms), but did not differ from each other. Although reflected in different measures, in both vision conditions we see evidence for the predictable conclusion that errors are generally associated with faster movements – consistent with the overall suggestion that, on error trials in particular, action is preempting perceptual identification.

Error Severity. Given the surprising finding that the rate of Uncaught errors was completely unaffected by the Yoked-Vision manipulation, we sought to examine these errors more closely to see if there might be more subtle differences. In particular, we assessed whether or not there were differences between vision conditions in the number of intervening moves on Uncaught error trials. In Figure 2.12 we plot the proportion of Uncaught Error trials having differing numbers of intervening moves, for both Full-Vision and Yoked-Vision conditions. The data were analyzed with a Vision (Full, Yoked) by Intervening Moves (1, 2, 3, 4, 5-9, 10+) repeated measures ANOVA. Predictably, because total proportions for both Vision groups were constrained to 1.0, there was no main effect of Vision ($F < 1$). More importantly, there was both a significant effect of Intervening Moves, $F(5, 95) = 29.4$, $MSE = .030$, $p < .001$, and a significant interaction, $F(5, 95) = 30.0$, $MSE = .024$, $p < .001$. This interaction was explored by conducting a paired-samples t-test at each level of the Intervening Moves variable. Correcting for multiple comparisons, these tests confirmed what is visually apparent in the figure – that Uncaught Errors under Yoked-Vision are more likely relative to Full-Vision to have only a single intervening move between the first and last target moves, $t(19) = 7.218$, $p < .001$, and less likely relative to Full-Vision to have 5 or more intervening moves, $t_s > 4.3$, $p_s < .001$.

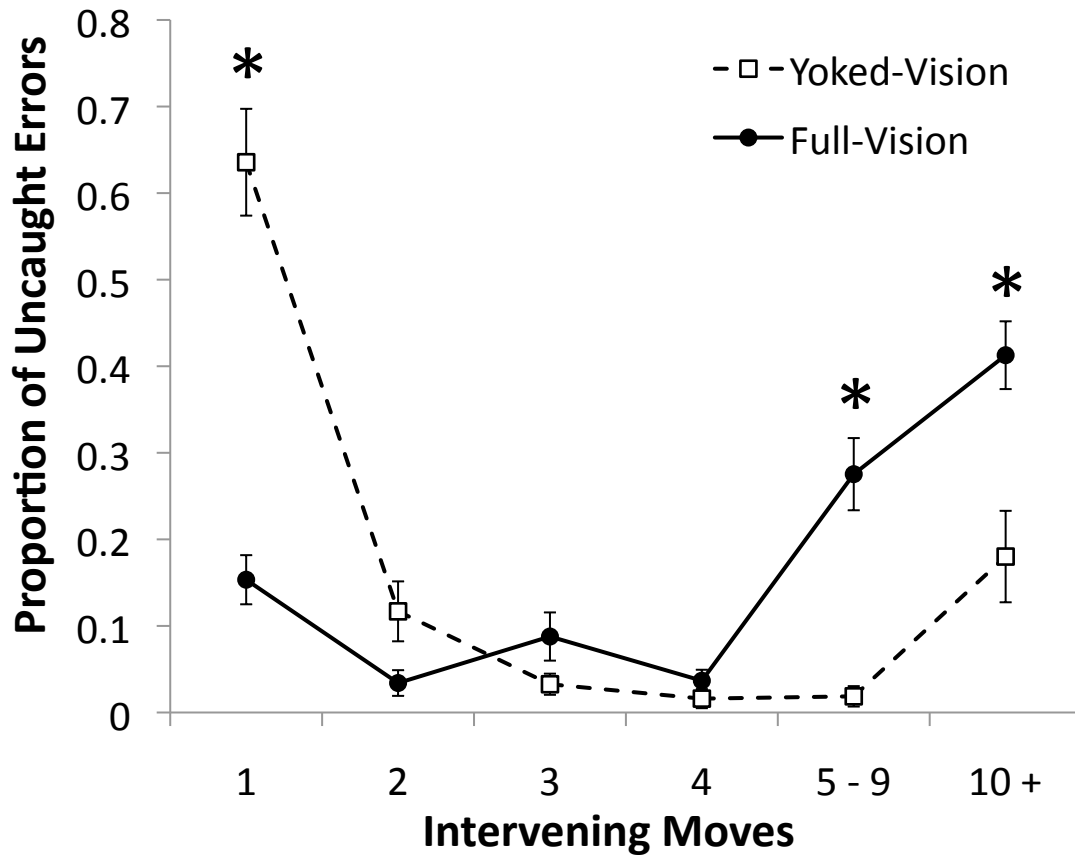


Figure 2.12 Distribution of error severity for Uncaught errors (indexed by the number of intervening moves between initial and final movement of the target), plotted for Yoked-vision (dashed line) and Full-vision (solid line) conditions. Error bars depict one standard error of the mean. * $p < .001$.

This finding is initially counter-intuitive, as the Yoked-vision condition does not afford re-inspection of discarded items to the same degree as the Full-vision condition; in the Yoked-vision condition an item's identity is no longer visible as soon as it is released. Consequently, one might expect that once an error is made in the Yoked-vision condition, it should be much less likely for the participant to catch the error quickly. The finding can be explained, however, by postulating that the processing of item identity occurs primarily internally, and consequently may persist even after the physical stimulus is no longer available. In this case, the likelihood of successfully noticing an error would depend on the ability of this residual processing to complete prior to being disrupted by new information. Consequently, the Yoked-vision condition may be seen as protective of this persisting identity processing, as the rate of incoming disruptive information is reduced. In contrast, in the Full-vision condition there is both an increased overall perceptual load from the display as a whole, as well as the opportunity for perceptual systems to begin processing the next candidate earlier (i.e., before it is selected for movement). Both of these factors would increase the likelihood of masking or otherwise disrupting the residual trace of the erroneously rejected target. Such an account is also consistent with the finding in Experiment 1 of differences in Uncaught error rates across item similarity. In that instance, the highly dissimilar item set was protective against errors for two reasons: 1) the items could be identified more quickly and reliably, and 2) the reduced perceptual overlap between items would be protective against disruption of residual processing.

2.4 Experiment 4

In the preceding experiments we have argued that the unpacking error results from a counter-intuitive behavioral strategy during manually-assisted search, wherein the motor processes responsible for unpacking the display are largely decoupled from perceptual analysis of the items being manipulated. Despite the fact that the participant's sole task is to locate a target item and reject non-target items, we find consistent evidence that the motor system regularly acts on items before they have been

classified as target or non-target. There is however, an important alternative that must be addressed before this account can be fully endorsed. In particular, it is critical to verify that participants do in fact give themselves the opportunity to inspect the target item prior to an error. That is, one could imagine that the unpacking error is a simple consequence of a momentary distraction during which participants look elsewhere during the period of target selection and rejection. To assess this hypothesis, in Experiment 4 we repeat the standard (Full-Vision) unpacking task, while concurrently recording eye-movements. We can thereby directly evaluate whether or not participants have had an opportunity to examine the target prior to erroneously rejecting it.

Methods

Subjects. Twenty undergraduate students (12 female, 8 male) from the University of Waterloo participated for course credit. All participants reported normal or corrected-to-normal visual acuity, and normal color vision.

Displays. Search items were taken from the Similar item set in Experiment 1 and all subsequent experiments. Likewise, the display generation process was identical to that used in prior experiments.

Procedure. Each trial began with the appearance of the search display. Participants were instructed to find the target as quickly as possible, the template for which was shown in the green box on the right side of the screen. They could use the mouse to move items anywhere on the screen to uncover occluded items. The trial was terminated when participants found the target and dragged it onto the green box containing the target template. The next search trial commenced after a 250 ms delay.

Participants performed 5 practice trials, then completed two blocks of 75 trials each, with calibration of the eye-tracker prior to each block of experimental trials. An equal number of each Set Size (12, 24) was intermixed across trials. The initial configuration of the items, as well as the grab time, drop time, and drop coordinates of each moved item were recorded. In addition, both cursor and eye-movements were recorded throughout the task.

Apparatus. The experiment was created in MATLAB, using version 3 of the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), and run on an Apple mini, with OS X 10.6.4 and a 2.4GHz Intel Core 2 Duo processor. The stimulus displays were presented on a 19" Dell 1905FP monitor at a resolution of 1280 by 1024 at a distance of 55 cm. Eye-movements were recorded using a desktop-mounted Eyelink 1000 system (SR Research), with participants' heads stabilized by a chin and forehead rest. A nine-point calibration routine was used, with acceptance criteria of less than 0.5° average deviation, and less than 1.0° maximum deviation.

Results

Response Times. Response Times were again log-transformed to correct for positive skew. Mean RTs were nearly identical to those from matched conditions in Experiments 1, 2, and 3 (Set Size 12: 4.831 sec (SE: 0.108); Set Size 24: 8.417 sec (SE: 0.228).

Unpacking Errors. Overall, Caught errors were produced on 7.2% of trials, and Uncaught errors on 8.0% of trials. These error rates are plotted across Set Size in Figure 2.13, and were analyzed with an Error Type (Caught, Uncaught) by Set Size (12, 24) repeated measures ANOVA. No effects reached significance (largest $F = 2.7$, $p = .115$).

Eye Movements. We first provide a qualitative assessment of the spatial pattern of overt attention surrounding a critical move. For this purpose, we first normalize the data to a common, move-centred reference frame (Figure 2.14 and following description).

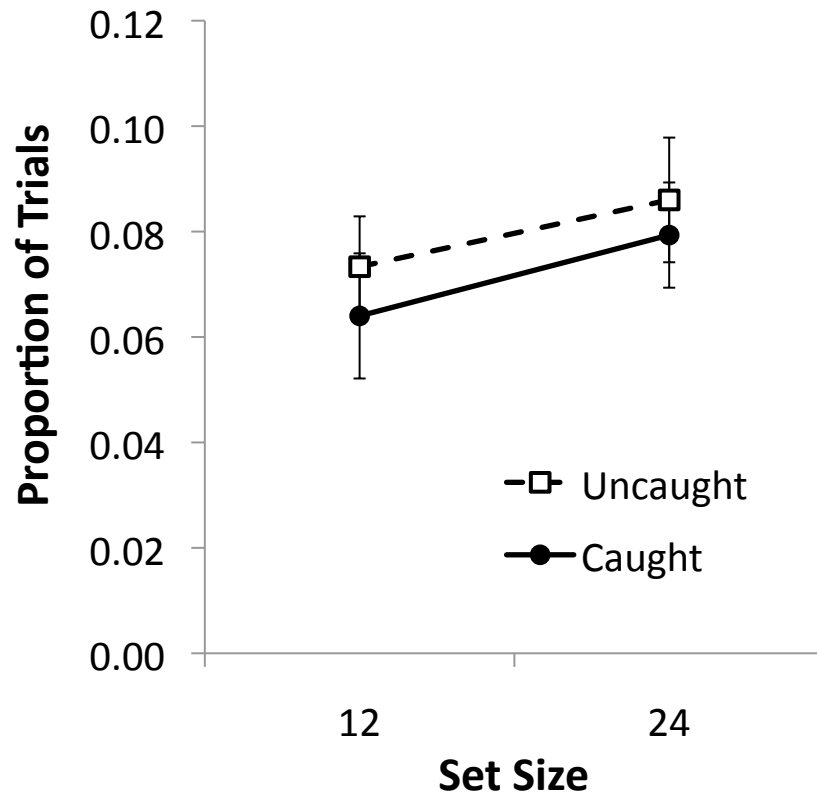


Figure 2.13 Proportion of Trials in Experiment 4 having Caught errors (solid line) and Uncaught errors (dashed line), plotted across Set Size. Error bars depict one standard error of the mean.

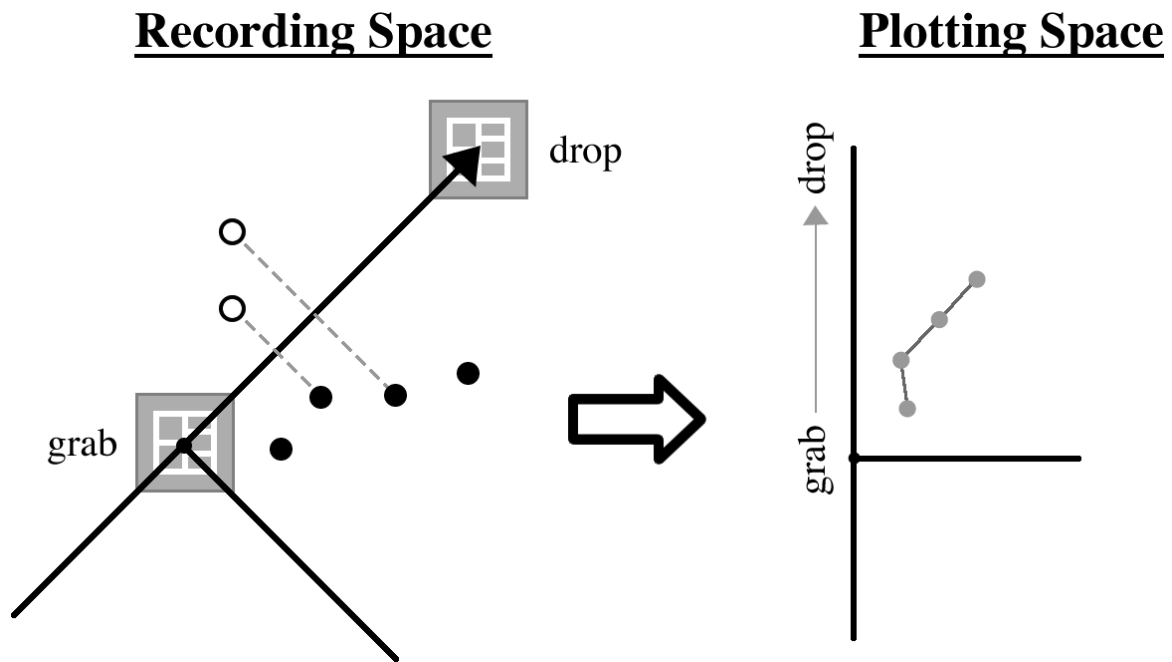


Figure 2.14 Data alignment procedure for eye-tracking samples. Samples were aligned relative to individual moves. The Recording Space (left) refers to the native on-screen coordinate system. Within the Recording Space, each move defined a vector from the grab location to the drop location. This vector was taken as the positive y-axis for Plotting space, and samples were reflected about this axis. All samples surrounding a given type of move (e.g., first target move on Uncaught error trials) were translated into this common reference frame and then averaged into traces. The resulting ‘Plotting Space’ can be understood as follows. The starting position for a move is at the origin, and the drop position is at some positive distance up the y-axis. Negative values on the y-axis indicate movement in the opposite direction from the actual move. The x-axis has only positive values, and represents distance orthogonal to the movement vector.

For each critical move, we first compute the oriented vector from the grab point of the move to the drop point of the move. Setting the grab location as the origin, this vector is taken as our positively-oriented y-axis ('move axis'), and the orthogonal vector as our x-axis ('lateral axis'). All eye and mouse samples considered in relation to a given move are registered into this move-centred reference frame. While the move axis is meaningfully signed (positive values toward the drop location, negative values away from the drop location), the lateral axis is not. Consequently, we collapse our samples into the two positive lateral quadrants by reflecting the points from the negative quadrants about the move axis. Following these transformations, we obtain a common space in which to compare eye- and mouse-movements for the period preceding, during, and following a given movement.

In Figure 2.15 we show mouse (left side) and eye (right side) movements for the period preceding (trace 1) and during (trace 2) the trial-terminating target move on Correct trials. The beginning of each trace is indicated by a filled circle. The grey disc centred at the origin indicates the spatial extent of the target item before it is moved (the enclosed rectangle indicates the size of an individual virtual card, while the enclosing circle indicates the possible area covered across rotations). The empty rectangle and enclosing circle at the top left of each plot indicates the destination. Correct trial-terminating moves are easily interpretable. The mouse first moves onto the target item, then moves the item to its destination. The eye is slightly ahead of the mouse, starting on the item then moving away towards the drop location (the response box, for these trials). The eye continues toward the drop location following movement onset (beginning of trace 2), then terminates near the drop location.

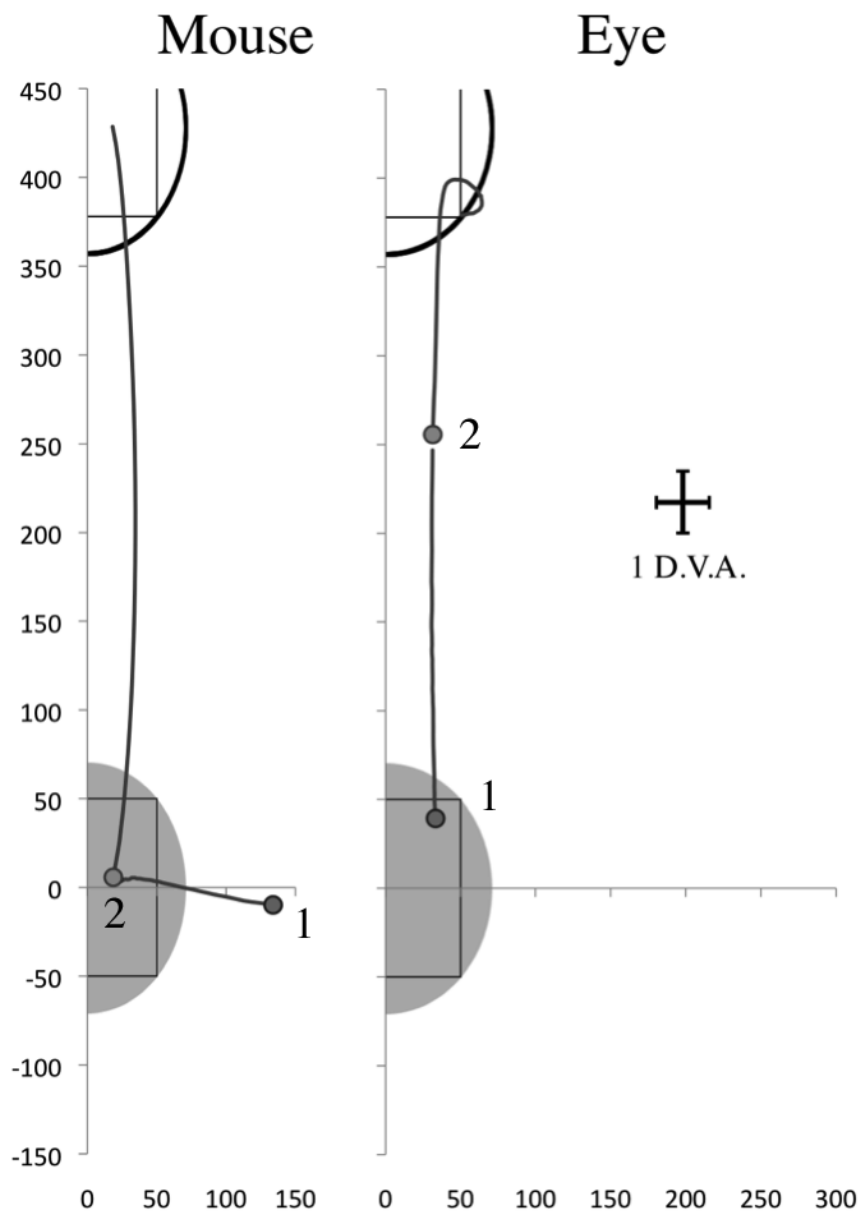


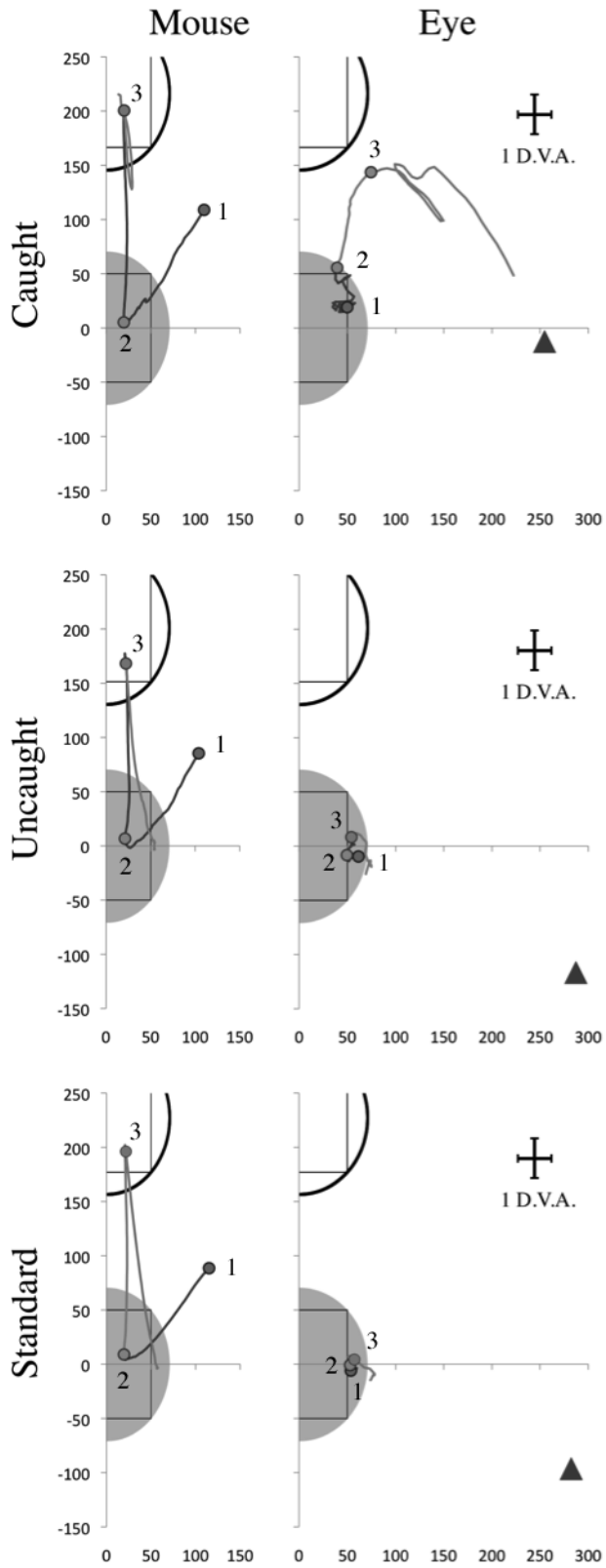
Figure 2.15 Mouse (left) and Eye (right) movement traces relative to the final, trial-terminating target move on correct trials (refer to Figure 2.14 and text for description of the plotting space). The grey disc and enclosed rectangle at the origin indicate the starting position of the target, while the empty disc and enclosed rectangle at the top left of each plot indicate the drop position of the target (for these moves, this is the response box). Traces are plotted for the period prior to the movement (1) and for the period during the movement itself (2). Numbered circular markers indicate the beginning time points for each trace.

Of even greater interest are the error trials, for which the first target moves are plotted in Figure 2.16 along with a Standard move for comparison. In these figures, we also plot a small filled triangle to indicate the approximate location of the response box. Mouse behaviour is highly similar across move types, with the exception of the post-move trace (trace 3) on Caught errors. For all three move types, the mouse moves onto the item (trace 1), then moves the item directly towards the drop location³ (trace 2). For both Standard moves and Uncaught errors, the mouse subsequently returns to the general neighborhood of the grab location (trace 3). For Caught errors, the mouse begins to move back toward the grab location then reverses mid-flight to return to the erroneously rejected target. Eye movements are even more informative. For both Standard moves and Uncaught errors, we see that the eye begins and remains in the general neighborhood of the grab location. In other words, there is no indication that participants give much attention to the terminal location, or to the item while in motion. For Caught errors, in contrast, the eye is near the grab location prior to the move, begins to track the item in motion, then diverges toward the response box – perhaps to verify the target template – reverses once more to reassess the item’s identity, then finally moves again toward the response box, presumably for a final targeting of the now-identified target. With these qualitative descriptions in mind, we next examine more quantitative measures.

Time on Target. Of focal importance is to determine whether or not participants are in fact attending to the target location prior to moving it. To this end, we computed the cumulative time-on-target during the period preceding the grab time for the target move and following the drop time of the preceding move. This measure is plotted for Correct trials, Caught errors, Uncaught errors, and for a comparison Standard move in Figure 2.17. There are two important features of this data to highlight. First, and most critical, we see that even in the case of Uncaught errors participants spend

³ Examining the movement direction in comparison to the approximate response box location, we see a good replication of the results from Experiment 3 – the initial target move is directed approximately orthogonal to the response box, with a small bias to be moving in the opposite direction.

Figure 2.16 Mouse (left) and Eye (right) movement traces relative to the erroneous target move on Caught (top row) and Uncaught (middle row) trials, and relative to a typical non-target move during a correct trial (Standard move; bottom row). Traces are plotted for the period prior to the movement (1), during the movement (2), and following the movement (3). Numbered circular markers indicate the beginning time points for each trace. The filled triangles on the eye-movement panels (right side) indicates the location of the response box.



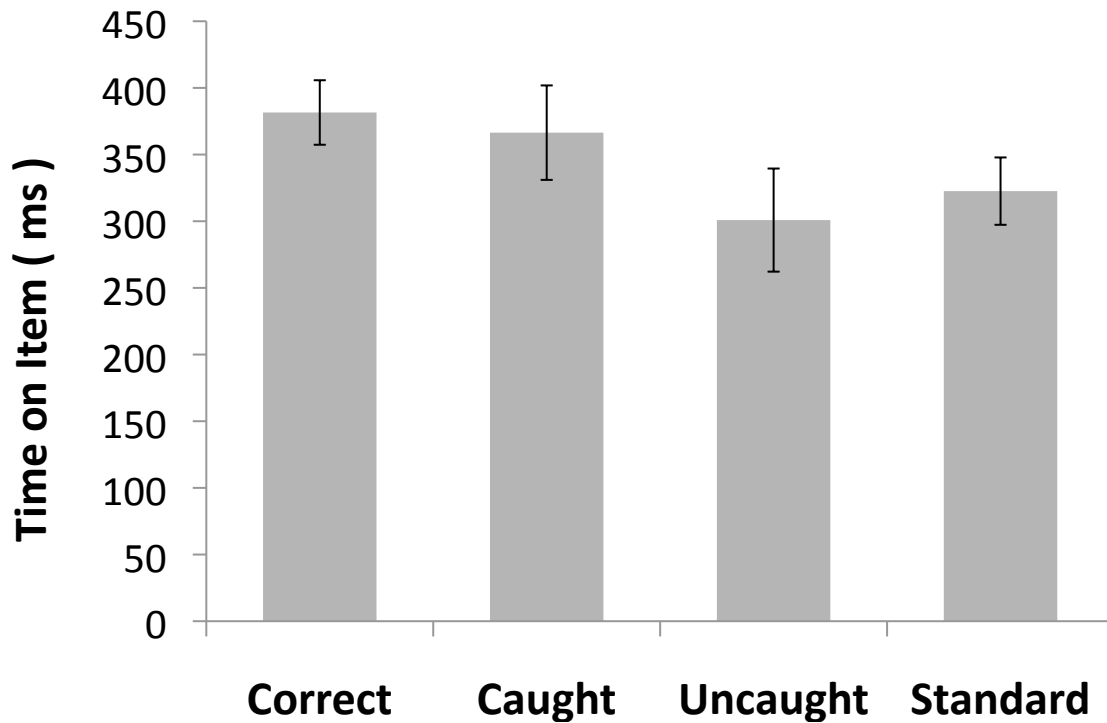


Figure 2.17 Average time spent looking at the target (ms) during the period preceding target movement (and following the previous movement). Plotted for the final, trial-terminating target move on Correct trials, for the first (erroneous) target move on Caught and Uncaught error trials, and for a typical non-target move on a correct trial (Standard). Error bars depict one standard error of the mean.

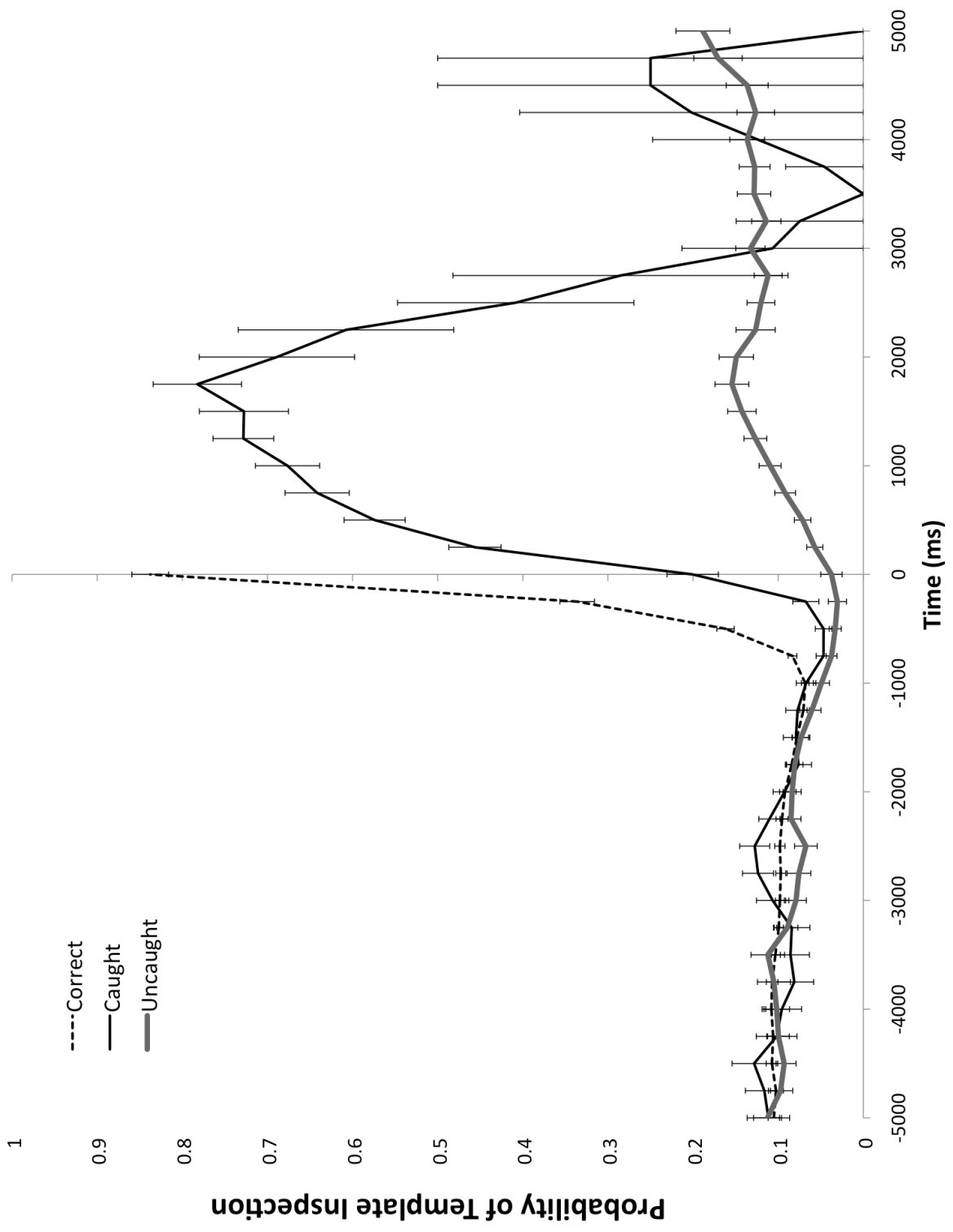
an average of 300 ms looking at the target. Consequently, we can rule out an account that posits the error as being a simple consequence of not having had opportunity to process the target prior to moving it. Notably, there is an important distinction to be held in mind between looking and seeing – the fact that the item has been foveated does not, by necessity, imply that it is being actively processed by the visual system (see e.g., Reichle, Reineberg, & Schooler, 2010). However, for present purposes, it is of most critical import that the observer has had ample *opportunity* to process the item (i.e., that failure to identify the target was not merely due to the target being inaccessible to the visual system). To assess potential differences between trial types, we conducted a one-way ANOVA on Time on Target. The effect of trial type was only marginal, $F(3, 57) = 2.2$, $MSE = 12,691$, $p = .095$. Nonetheless, we further evaluated paired comparisons between each of the trial types, using a Bonferroni correction ($\alpha = .008$). Only the difference between Correct and Standard trials reached significance at this level ($t(19) = 3.41$, $p < .005$), although the Correct vs. Uncaught comparison approached criterion ($t(19) = 2.76$, $p = .013$). We note however, that the total duration of the pre-move segment is also longer for Correct trials – likely due to the additional post-identification demands of response preparation. This suggestion is supported by an increased rate of template inspection prior to a correct trial-terminating move (see following analysis). Consequently, the modest increase in pre-move time-on-target for Correct trials is likely reflective of revisitation following template inspection, or a simple consequence of increased idle time while the response is prepared, and unlikely to reflect any substantial increase in identification-related processing time.

Template Inspection. Examining the qualitative data suggests an additional possible account for the error. Although the results from the memory load manipulation in Experiment 2 suggested that the error was unlikely to be due to a failure of memory for the target, the pattern of eye-movements for Caught errors in the present experiment certainly indicates that participants feel the need to confirm the target identity – suggesting that the stored target template is imperfect. Consequently, it is

reasonable to suggest that the occurrence and severity of unpacking errors could be related to the strength of the target representation, which in turn should be related to how recently the physical target template has been inspected. Correct trials would result when the template has been most recently inspected, followed by Caught errors when the template has been inspected only recently enough to provide a partial match or a ‘hunch,’ and Uncaught errors resulting when the template has not been inspected recently enough to be functional. Alternatively, the stored template may be equally reliable across trial types, with the differential behavioral outcomes resulting from differences in the quality of the perceptual input – a notion consistent with the pattern of time-on-target data presented above. To evaluate these alternatives, we examined the probability of template inspection surrounding a critical move. If errors result from differential template quality, we should see the probability of template inspection prior to a move increase as we examine Uncaught, Caught, and Correct moves. Conversely, if the probability of template inspection is undifferentiated across trial types, then it is unlikely that differences in stored template quality are responsible for the errors.

In Figure 2.18 we plot for each trial type the probability that a participant is looking at the target template during the five seconds preceding and following (where applicable) the target move. At time zero, we plot this measure for the midpoint of the target move. Correcting for multiple comparisons, we find that the likelihood of fixating the template on Correct trials begins to increase relative to both types of error trials approximately 750 ms prior to onset of the movement. This is likely to reflect verification of the target identity, and preparatory targeting of the trial-terminating movement. Significant differences between Caught and Uncaught errors emerge only following movement onset (i.e., at time zero and thereafter). From these results, we see that differences in pre-movement template checking behaviour do not appear to predict errors, and certainly do not differentiate between Caught and Uncaught errors. Instead it appears that the likelihood of template inspection increases in response to the target, either for verification or for movement-targeting purposes.

Figure 2.18 Probability that the target template (co-extensive in space with the response box) was being inspected at times surrounding movement of the target (midpoint of the movement aligned to time zero). The sole target move was used for Correct trials (hashed line), while the first target move was used for Caught errors (thin black line) and Uncaught errors (thick grey line). Values were computed for the 5 seconds preceding and following the move. Correct trials (hashed) terminate following the target move, and so do not contribute data to the post-move period. Error bars depict one standard error of the mean.



2.5 Experiment 5

Although there are reasonable grounds for differentiating between Caught and Uncaught errors, as evidenced by meaningfully dissociable behavioral precedents and outcomes, they can also be considered to lie on a spectrum of error severity – with Caught errors being, by definition, equivalent to Uncaught errors with zero intervening moves. In this light, it is interesting to note that the eye-movement data reported above indicate that participants had some tacit awareness of the error on Caught error trials, apparently beginning to move the eye towards the target template and response box even while the erroneous movement was in progress. It is of interest then, to evaluate whether or not there are similar but more subtle indications of error awareness on Uncaught error trials. One candidate measure is readily available from the error monitoring literature. In particular, post-error slowing has been observed to be dissociable from conscious awareness of an error (e.g. Hester, Foxe, Molholm, Shpaner, & Garavan, 2005; Hester, Simões-Franklin, & Garavan, 2007; Rabbitt, 2002). Although typically evaluated at the trial level, the nature of the unpacking task enables us to evaluate post-error slowing at the level of individual moves within a given trial. In Experiment 5, we replicate the standard unpacking task and evaluate average movement speed for trials preceding and following an Uncaught error.

Methods

Subjects. Thirty undergraduate students (25 female, 5 male) from the University of Waterloo participated for course credit. All participants reported normal or corrected-to-normal visual acuity, and normal color vision.

Displays and Procedure. Search items, display generation, and trial procedures were identical to those used in Experiment 4. Participants completed 160 search trials, with an equal number of each Set Size (12, 24) randomly intermixed. Participants performed 5 practice trials followed by 160

experimental trials. The initial configuration of the items, as well as the grab time, drop time, and drop coordinates of each moved item were recorded.

The experiment was created in MATLAB, using version 3 of the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), and run on an Apple mini, with OS X 10.6.4 and a 2.4GHz Intel Core 2 Duo processor. The stimulus displays were presented on a 19" ViewSonic VA1912wb monitor at a resolution of 1440 by 900 at a distance of 55 cm.

Results

Outliers. Response times on a small number of trials were found to be very large (some exceeding 60 seconds). Closer inspection revealed that generally these long times did not result from a disproportionate number of moves in the trial, but instead from a single very long delay between terminating one move and beginning the next. It is unlikely that these pauses could occur while participants remained on task. Consequently, we removed trials on the basis of a conservative move-latency outlier threshold. Specifically, we removed any trial on which the delay between any two moves was 10 standard deviations or more from the subject's mean. This resulted in the removal of 1 trial from nine of the subjects, 2 trials from three of the subjects, and no trials from the remaining 18 subjects. Response times on the excluded trials were on average more than 30 seconds longer than the mean response times on the remaining trials.

Response Times. The distribution of response times in this task was heavily skewed. The response times plotted and analyzed are therefore the anti-logs of the mean log-RTs. Overall response times were consistent with previous experiments (Set Size 12: 4.899 sec (SE: 0.141); Set Size 24: 7.850 sec (SE: 0.277)).

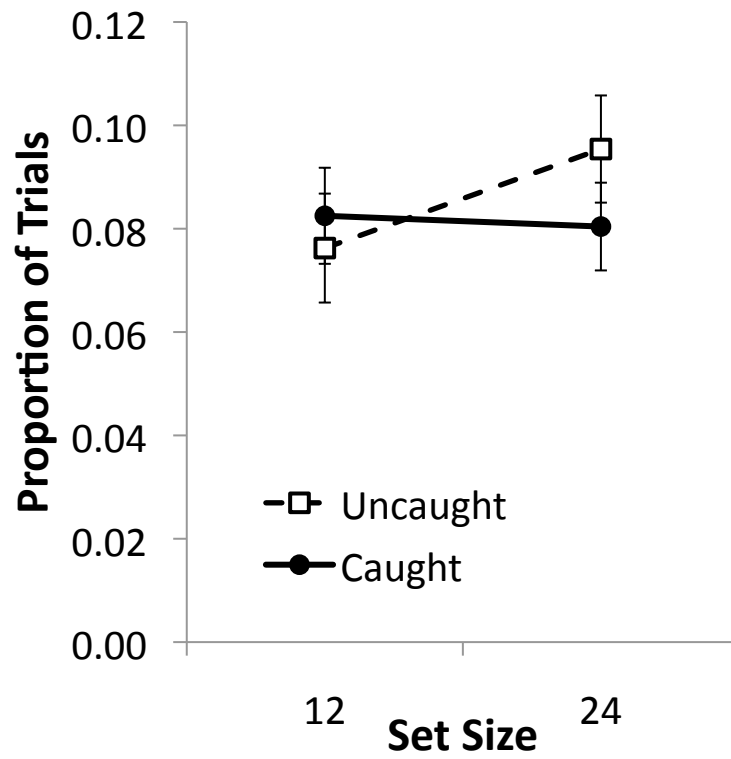


Figure 2.19 Proportion of trials in Experiment 5 having Caught errors (solid line) and Uncaught errors (dashed line), plotted across Set Size. Error bars depict one standard error of the mean.

Unpacking Errors. Caught and Uncaught error rates are plotted in Figure 2.19, and were analyzed with an Error Type (Caught, Uncaught) by Set Size (12, 24) repeated measures ANOVA. No effects reached significance (largest $F = 3.0$, $p = .094$).

Post Error Slowing. To assess whether post-error slowing is observed following Uncaught errors, we evaluated the characteristics of the eight moves prior to an erroneous target move, as well as the eight moves following the error⁴. In general, both move latencies (the time between dropping the previous item and grabbing the current item) and move durations (the time between grabbing an item and dropping it) were found to be highly variable, particularly near the ends of trials. To obtain more stable estimates of these values surrounding an error, we grouped lags in pairs (i.e. E-4 & E-3, E-2 & E-1, E+1 & E+2, E+3 & E+4, etc.; reported hereafter as E-8, E-6, E-4, E-2, E+2, E+4, E+6, E+8). In addition, individual subject means were included in the analyses only when based on a minimum of three samples. Given these criteria, the nine collapsed lag values had the following sample sizes: 19, 22, 26, 28, 29, 29, 28, 27, 25, with the earliest lag (E-8) being least well represented. Lags closest to the error move were, predictably, the best sampled. Values for the missing cells were imputed using a linear trend point estimation, with samples ordered on the basis of values observed at the error move, which had no missing cells. One subject made no errors, and so was not included in the analysis. Finally, we note that because move latencies and durations changed noticeably (in both magnitude and variability) across individual trials, a meaningful baseline could not be produced. Consequently, we evaluate only the raw values across lags, with particular focus on local changes surrounding the error. Figure 2.20 shows the lagged values for both move latencies (panel A) and move durations (panel B).

⁴ Reasoning that both the first and last moves in a given trial are qualitatively different from the remaining moves, these moves were not included in the analysis.

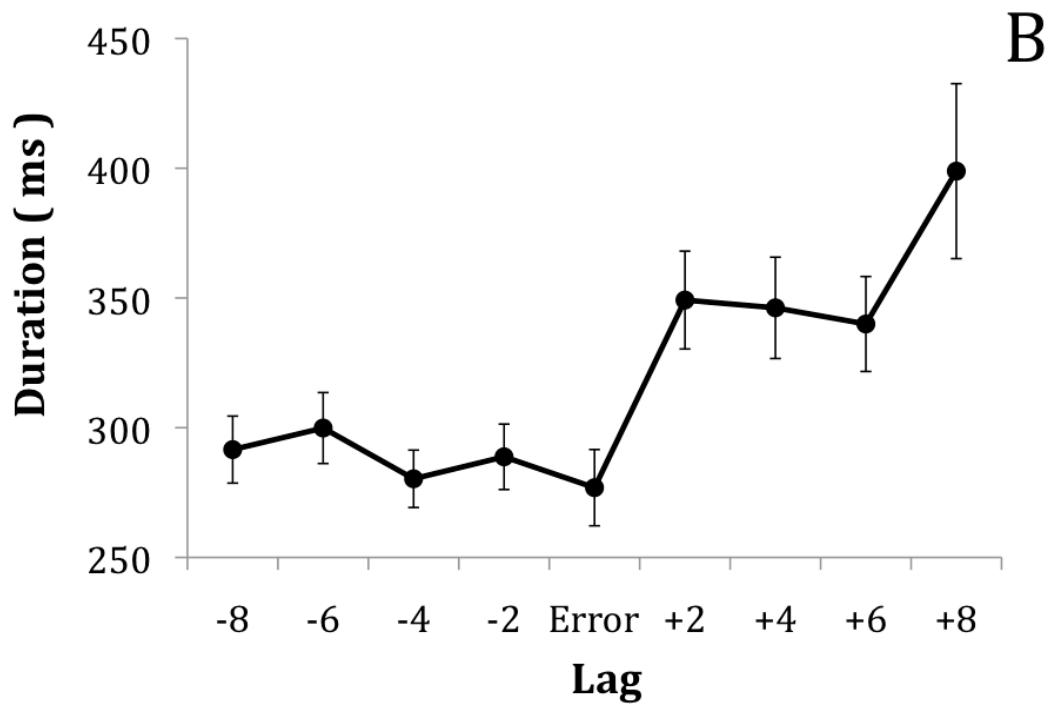
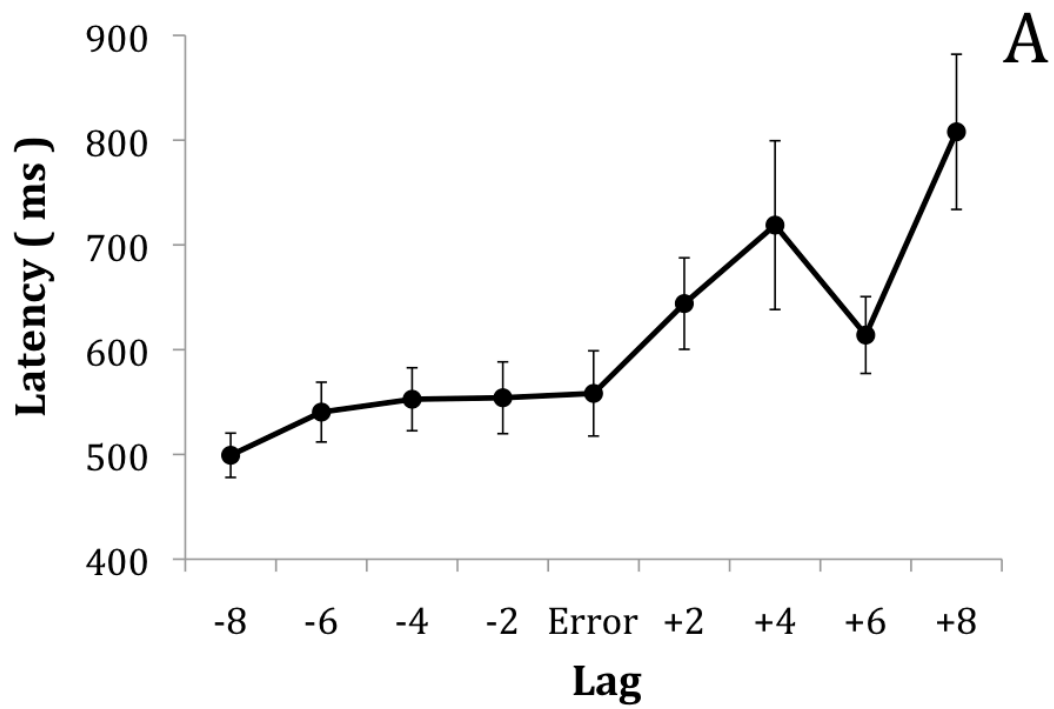


Figure 2.20 Move latencies (A) and durations (B) preceding, during, and following an Uncaught error. Lags refer to moves within a given error trial. Error bars depict one standard error of the mean.

Move characteristics were evaluated by conducting an Order (Pre-error, Post-error) by Lag (4 levels) ANOVA for both Latencies and Durations. Post-error slowing was clearly demonstrated in the data, with Post-error values significantly greater than Pre-error values for both Latency: $F(1,28) = 31.00$, $MSE = 47,668$, $p < .001$, and Duration: $F(1,28) = 23.86$, $MSE = 11,386$, $p < .001$. To assess whether these differences result from discontinuities at the error move, as is suggested by visual inspection, and not simply from a gradual increase in values over time, we performed a paired-samples t-test between the values on the Error move, and the values both immediately preceding and immediately following the Error move. Consistent with an error-induced discontinuity, pre-error values did not differ from the error values (Latency: $t(28) = .127$, $p > .85$; Duration: $t(28) = 1.188$, $p > .24$), but post-error values were significantly greater than the error values (Latency: $t(28) = 2.317$, $p < .05$; Duration: $t(28) = 4.411$, $p < .001$). That we observe a qualitative and measurable shift in behaviour immediately following an Uncaught error, strongly supports the notion that the error is in fact recognized at an implicit level. Consistent with our findings in Experiment 4, the apparent implicit recognition reported here further supports the conclusion that the target item is being processed prior to being moved on error trials.

2.6 Experiment 6

Based on the preceding studies, we have suggested that the unpacking error arises directly from the unique interaction of motor and perceptual processes in the Unpacking task. In particular, contrary to intuitive expectations, it seems that motor systems are not attendant to perceptual systems while participants complete the search task. Instead, motor actions are frequently initiated and concluded before perceptual processes have had an opportunity to adequately identify the target of action. This *perceptuomotor incoordination* account is consistent with research demonstrating that visual processing can be tuned to specific aspects of a task to the detriment of others (e.g., Ballard, Hayhoe, & Pelz, 1995; Hayhoe, Bensinger, & Ballard, 1998; Hoffman, Landau, & Pagani, 2003); that an item

has been perceptually processed to support action does not imply that information about its identity has also been processed. Likewise, the more specific *motor-speeding* hypothesis for the error – that the incoordination is in the direction of motor processes unfolding too quickly for perceptual processes – is supported by research indicating that motor sequences are regularly planned several moves ahead, and these planned actions are able to bias spatial attention (e.g., Baldauf & Deubel, 2008; 2010).

While the proposed perceptuomotor incoordination hypothesis is well supported by the data presented thus far, in order to be confident in generalizing these results to other contexts, it is important to verify that this incoordination is a consequence of the general characteristics of the task – and not merely an artifactual consequence of the particular instantiation presented here. To this end, in Experiment 6, we manipulate two aspects of the experiment that might have artificially induced incoordination during the task: 1) the method of interaction, and 2) instructional biases toward speeding.

First, we note that there are potentially important differences between the use of a mouse (an ‘indirect pointer’) and use of the hand (a ‘direct pointer’). Although there is good reason to believe that use of a mouse may be comparable in many ways to use of the hand (e.g., Bassolino, Serino, Ubaldi, & Ladavas, 2010; Goldenberg, & Iriki, 2007), there are important differences that could lead to increased incoordination while using a mouse relative to using the hand. Of particular importance is the fact that movements of the on-screen cursor are greatly amplified relative to the movement of the physical mouse. In this sense, by minimizing the energetic demands for a given movement, use of a mouse may facilitate speeded movements. Under the specific motor speeding incoordination hypothesis for the unpacking error, this feature of the mouse interface could result in an increased rate of error relative to more naturalistic interfaces. To evaluate this concern, we compare performance on

the unpacking task while using a mouse (indirect pointer) to performance while using a touch screen (direct pointer).

A second factor of importance to the unpacking error concerns the influence of instructions on participant strategies. A critical assumption underlying the ecological validity of the unpacking error is that the excessive motor speeding relative to perceptual limits reflects a naturally occurring strategic decision (though likely unconscious) made by participants. In contrast, it is possible that the degree of speeding was biased by use of traditional search instructions to locate the target on each trial as quickly as possible. Consequently, in addition to the interface manipulation, we also include a between-subjects instructional manipulation. Participants performed the unpacking task under one of three instruction conditions (refer to methods for precise wording): 1) ‘traditional’ instructions, encouraging speed, 2) unbiased instructions, not mentioning speed, or 3) explicit slowing instructions. If the unpacking error results only because of an unnatural induction toward speeded responding, then participants performing the task under slowing instructions, and instructions not emphasizing speed, should be markedly slower at the task, and should produce fewer errors.

Methods

Subjects. Sixty undergraduate students (39 female, 21 male) from the University of Waterloo participated for course credit. All participants reported normal or corrected-to-normal visual acuity, and normal color vision. The instructional manipulation was applied across successive cohorts, with 20 subjects in each.

Displays. Search items were taken from the Similar item set in Experiment 1 and all subsequent experiments. Likewise, the display generation process was identical to that used in prior experiments.

Procedure. Each trial began with the appearance of the search display. Participants were instructed to find the target item, the template for which was shown in the green box on the right side of the

screen. They could move items anywhere on the screen to uncover occluded items, in whatever order they wished. The trial was terminated when participants found the target and dragged it onto the green box containing the target template. The next search trial commenced after a 250 ms delay.

Three factors were varied in the experiment. An Instruction manipulation was administered between participants, with varying degrees of emphasis on speed. Twenty participants completed the task under each of three instructions: 1) Fast: *“Your task is to locate [the target] in the stack and to drag it onto the green target box. Try to find each target as quickly as possible,”* 2) None: *“Your task is to locate [the target] in the stack and to drag it onto the green target box,”* and 3) Slow: *“Your task is to locate [the target] in the stack and to drag it onto the green target box. While you are completing this task, it is important that you do not rush. Don’t worry about going too slowly. Take your time and think carefully about each move you make as you work on locating the target item in each trial”*. Pointer Type (Mouse, Touch) was blocked within participants and counterbalanced, so that each participant completed 80 trials using the mouse, and 80 trials using the touch screen (the cursor was not displayed during touch trials). Within each block of 80 trials, Set Size (12, 24) was randomly intermixed. Participants performed 3 practice trials for each Pointer Type followed by the 160 experimental trials. The initial configuration of the items, as well as the grab time, drop time, and drop coordinates of each moved item were recorded.

The experiment was created in MATLAB, using version 3 of the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), and run on an Apple mini, with OS X 10.6.4 and a 2.4GHz Intel Core 2 Duo processor. The stimulus displays were shown on a 21.5” Dell ST2220T monitor at a resolution of 1920 x 1080 at a distance of 55 cm, with the display surface positioned at an angle of approximately 35 degrees from horizontal. As the OS X operating system does not provide native support for touch input on the Dell ST2220T monitor, a third party driver was used (Touch Base Ltd., www.touch-base.com).

Results

Response Times. Response Times (RTs) were highly skewed, and so were adjusted using a log transform. The values plotted and analyzed are based on the anti-logs of the mean log RTs for each subject (Figure 2.21).

The data were analyzed with an Instruction (Fast, None, Slow; between) by Pointer Type (Mouse, Touch; within) by Set Size (12, 24; within) mixed factors repeated measures ANOVA. A main effect of Set Size, $F(1, 57) = 718.0$, $MSE = 1.097$, $p < .001$, and a significant effect of Instruction, $F(2, 57) = 5.94$, $MSE = 6.080$, $p < .005$, were observed, but no other effects reached significance (largest $F = 1.69$, $p = .194$). The effect of Instruction was further resolved by running a separate ANOVA for each pair of Instruction conditions, revealing what is evident from the figure: RTs under Fast instructions were faster than under either None, $F(1, 38) = 8.09$, $MSE = 6.202$, $p < .01$, or Slow instructions, $F(1, 38) = 10.9$, $MSE = 5.307$, $p < .005$, whereas None and Slow instructions did not differ ($F < 1$, $p = .840$). These results indicate that the instructions to “*find each target as quickly as possible*” did prompt participants to go somewhat faster than they otherwise would have, which is important for subsequent considerations of the error data.

Number of Moves. As with RTs, the number of moves required during search were subjected to a log-anti-log transform to correct for skew prior to plotting and analysis (Figure 2.22). The data were analyzed with an Instruction (Fast, None, Slow; between) by Pointer Type (Mouse, Touch; within) by Set Size (12, 24; within) mixed factors repeated measures ANOVA. Mirroring RTs, search required a greater number of moves under the larger Set Size, $F(1, 57) = 262.9$, $MSE = 1.075$, $p < .001$. Interestingly, in contrast to RTs, there was also a significant effect of Pointer Type, $F(1,57) = 22.4$, $MSE = 1.484$, $p < .001$, such that search using the Touch screen involved slightly more moves on average than did search using the Mouse. Given that RTs did not differ across Pointer Type, this

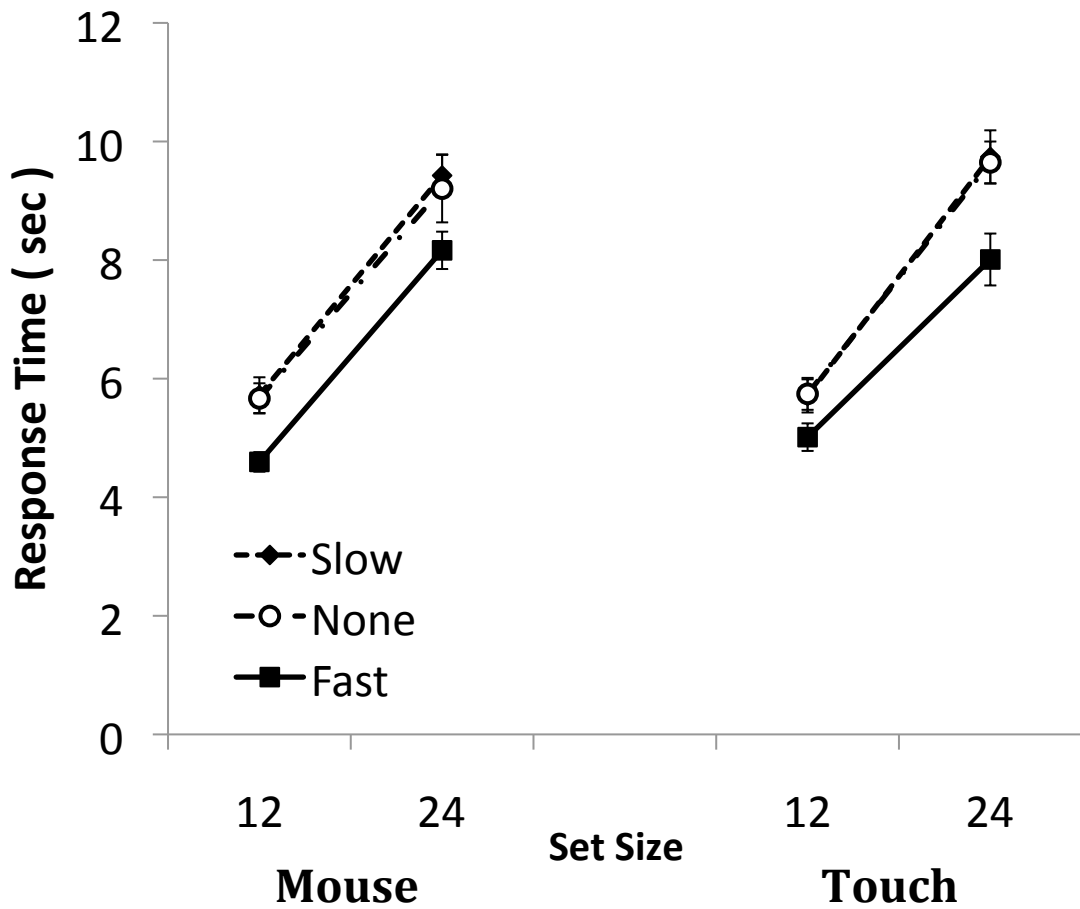


Figure 2.21 Response Times (seconds) for Experiment 6, plotted for each Instruction condition (Slow, None, Fast), across interaction methods (Mouse, Touch) and Set Size (12, 24). Error bars depict one standard error of the mean.

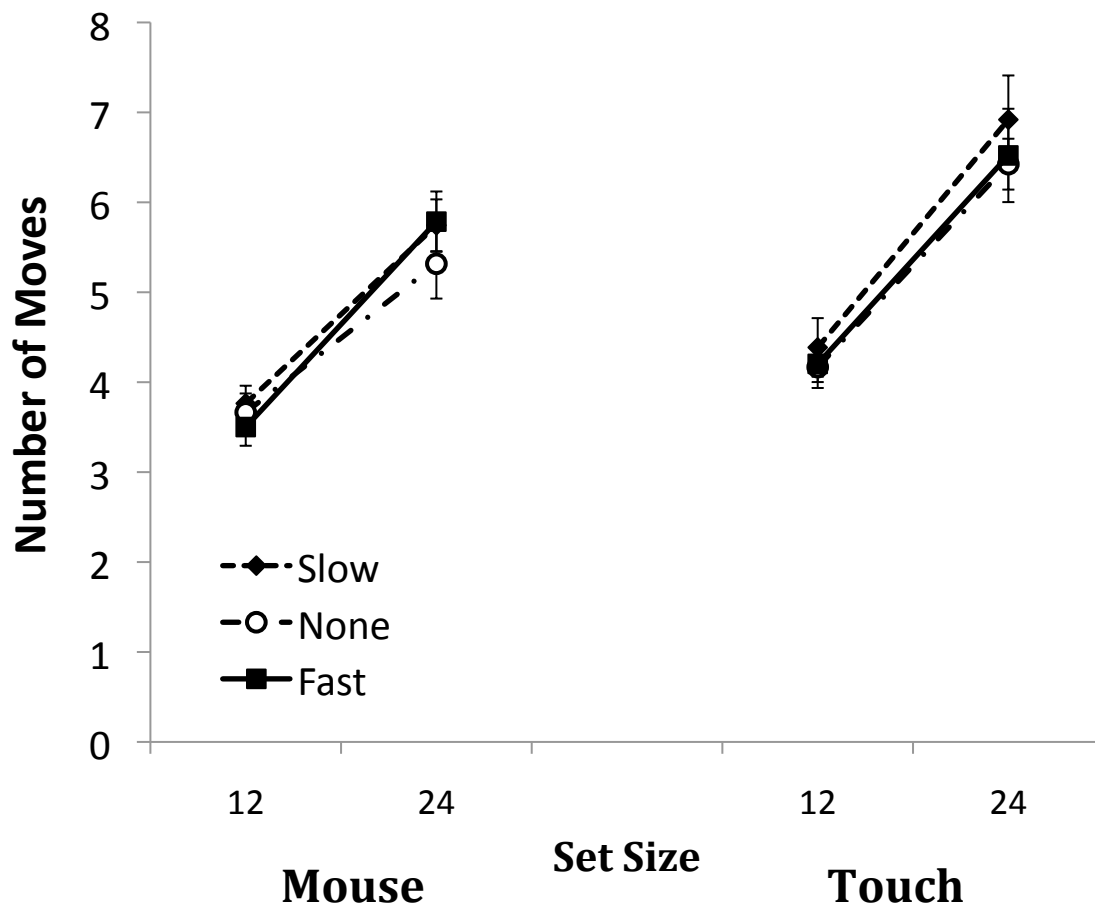


Figure 2.22 Number of moves per trial for Experiment 6, plotted for each Instruction condition (Slow, None, Fast), across interaction methods (Mouse, Touch) and Set Size (12, 24). Error bars depict one standard error of the mean.

finding indicates that each individual move while using the Touch screen was faster on average than the individual moves made while using the Mouse. No other effects reached significance (largest $F = 1.931$, $p = .170$); notably, this includes the absence of an effect of Instruction.

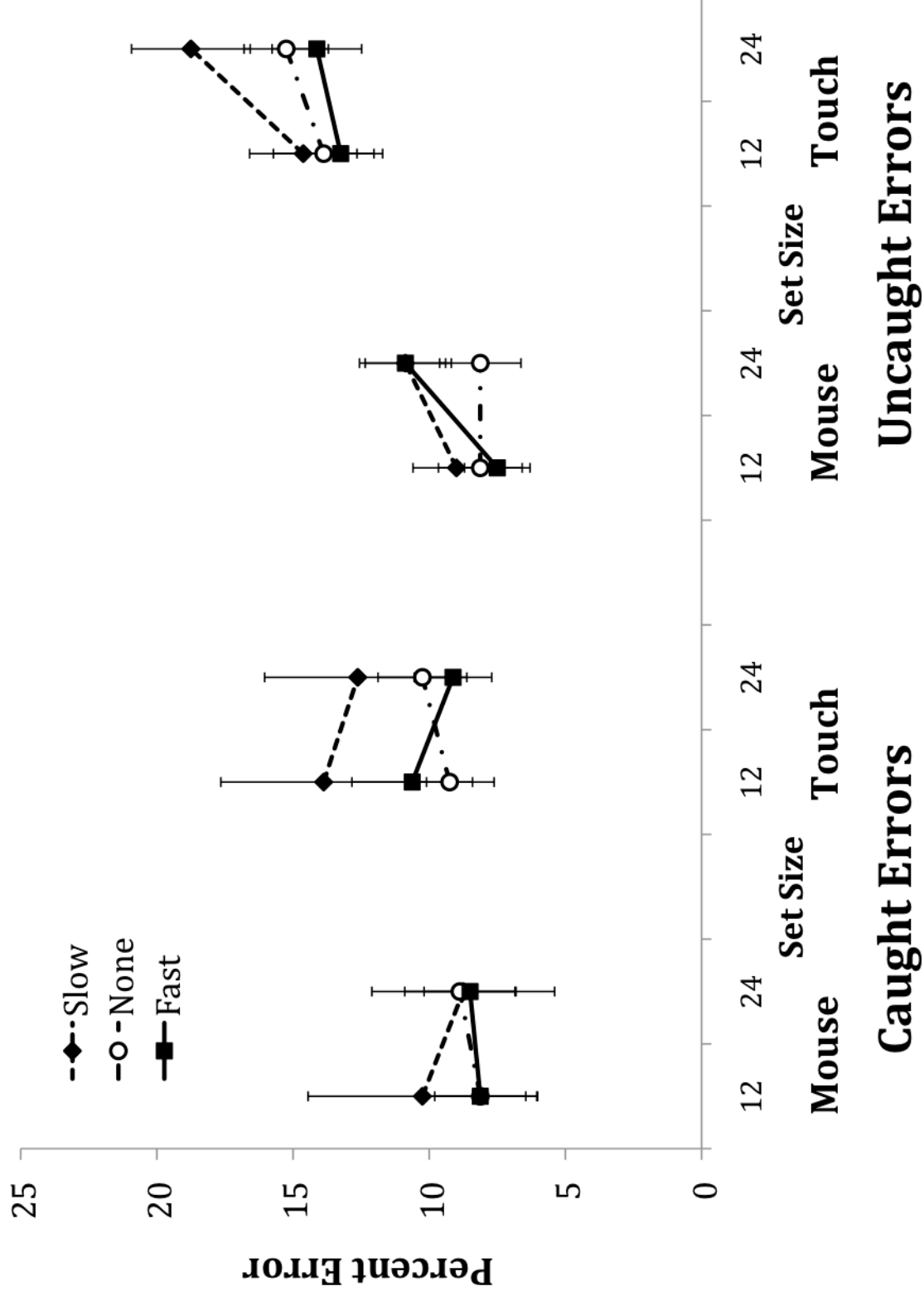
Unpacking Errors. The rates of Caught and Uncaught errors are plotted in Figure 2.23. The data were analyzed with an Instruction (Fast, None, Slow; between) by Error Type (Caught, Uncaught; within) by Pointer Type (Mouse, Touch; within) by Set Size (12, 24; within) mixed factors repeated measures ANOVA. We found no main effect of Instruction ($F < 1$, $p = .534$), nor any significant interactions with Instruction (largest $F = 2.040$, $p = .139$). There was however, both a small main effect of Set Size, $F(1, 57) = 4.58$, $MSE = 16.416$, $p < .05$, and a main effect of Pointer Type, $F(1, 57) = 39.7$, $MSE = 49.341$, $p < .001$, such that errors were more prevalent for the larger Set Size and for Touch and compared to Mouse conditions. Both of these effects were further qualified by interactions with Error Type (Set Size by Error Type: $F(1, 57) = 5.14$, $MSE = 30.648$, $p < .05$; Pointer Type by Error Type: $F(1,57) = 15.3$, $MSE = 27.027$, $p < .001$). These interactions were further examined by conducting a separate Instruction (Fast, None, Slow) by Pointer Type (Mouse, Touch) by Set Size (12, 24) ANOVA for Caught and for Uncaught errors. The effect of Set Size was present only for Uncaught errors, $F(1, 57) = 10.5$, $MSE = 21.435$, $p < .005$, and not for Caught errors ($F < 1$, $p = .590$). The effect of Pointer Type was observed for both classes of error, but appeared stronger for Uncaught errors, $F(1, 57) = 79.2$, $MSE = 26.320$, $p < .001$, than for Caught errors, $F(1, 57) = 5.74$, $MSE = 50.048$, $p < .05$. No other effects reached significance in these follow-up ANOVAs (largest $F = 1.272$, $p = .288$), or in the overall omnibus ANOVA (largest $F = 2.475$, $p = .121$).

Discussion

The foregoing results provide several important conclusions. First, despite the possible facilitation of speeded movements offered by the amplification inherent in a mouse interface, we found instead that use of a direct interface actually resulted in increased speeding – with a greater number of moves

made in the same total time. Consistent with the motor speeding hypothesis of the unpacking error, this increased rate of movement using the direct interface was associated with an increased rate of uncaught errors during search. These results clearly demonstrate that the unpacking error is not simply a result of using an indirect pointer, and that the likelihood of the error may if anything be attenuated by using less naturalistic interfaces. Second, we have shown that the *excessive* speeding that seems to cause the unpacking error is not a consequence of speeding instructions. Although a small increase in response times (~20%) was observed for None and Slow instructions relative to Fast instructions, implying that instructions did have some influence over participant behaviour, this increase did not translate to a measurable reduction in the rate of unpacking errors. Although this result provides an important demonstration that the unpacking error does not result because of an imposed strategy of speeding, it also poses a potential problem for the motor speeding hypothesis. In particular, despite measurable slowing under None and Slow instructions, the rate of the error did not decrease as would be predicted. However, the slowing itself was not particularly dramatic, and the error rates themselves have large variance, raising the possibility that there was simply not enough slowing to produce a detectable effect on error rates. To resolve this issue, in Experiment 7 we introduce a much stronger manipulation of motor speed.

Figure 2.23 Percent error for Experiment 6, with rates of Caught and Uncaught errors plotted separately. Error rates are plotted for each Instruction condition (Slow, None, Fast), across interaction methods (Mouse, Touch) and Set Size (12, 24). Error bars depict one standard error of the mean.



2.7 Experiment 7

In Experiment 6 we found that instructional manipulations had minimal impact on the speed at which participants completed the unpacking task. While this supports the conclusion that the unpacking error arises from naturally adopted strategies as opposed to instructional biases, it unfortunately does not allow us to draw strong conclusions regarding the motor speeding hypothesis itself. In Experiment 7, we address this issue more directly, by manipulating motor speed through the structure of the task itself. In particular, we introduce a ‘Forced Deposit’ condition, wherein participants are no longer able to freely arrange items as they remove them from the heap, but must instead place each item in a designated position on the screen. We reasoned that forcing participants to make movements towards a specific endpoint would result in greater attention to the movement as a whole, and a consequent slowing of each movement. Given the motor speeding hypothesis of the unpacking error, this slowing should result in a significant reduction in the rate of the unpacking error relative to the standard unpacking task (where movement endpoints are unconstrained).

Methods

Subjects. Twenty-four undergraduate students (18 female, 6 male) from the University of Waterloo participated for course credit. All participants reported normal or corrected-to-normal visual acuity, and normal color vision.

Displays. Search items were taken from the Similar item set in Experiment 1 and all subsequent experiments. Likewise, the display generation process was similar to that used in prior experiments, with some exceptions. First, Set Size was not manipulated in this experiment, so that every display consisted of 18 search items. Second, for trials in the new Forced Deposit condition, there was also a 2-by-9 empty grid arrayed along the top of the screen (Figure 2.24). Each cell matched the size of the items in the search display. Participants in this condition were required to place items into the grid, as described below.

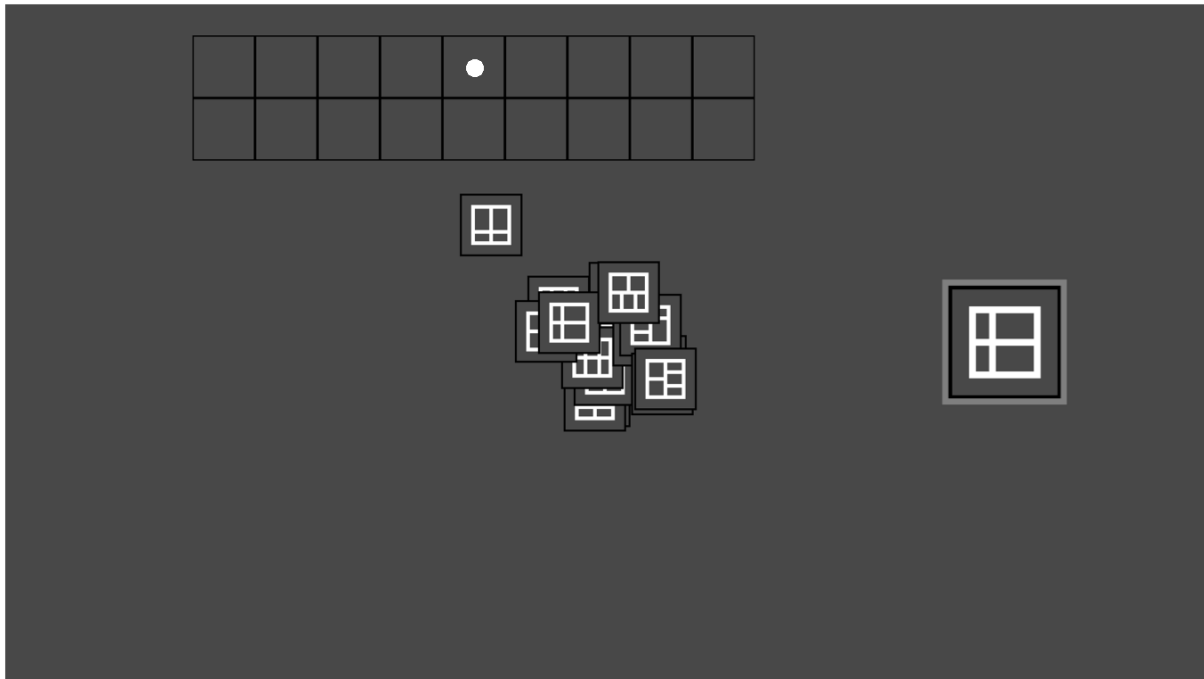


Figure 2.24 Example display from the Forced Deposit condition in Experiment 7. When an item was selected, a red dot (white in the figure) would appear in a random unoccupied location in the grid at the top of the display. Participants were required to place the selected item in that position; otherwise the item would return to the position it had prior to being selected. The target item could also be moved directly to the response box.

Procedure. Each trial began with the appearance of the search display. Participants were instructed to find the target item, the template for which was shown in the green box on the right side of the screen. Participants completed trials in two conditions. In the Normal condition, participants could move items anywhere on the screen to uncover occluded items, in whatever order they wished, as in the previous studies. In the Forced condition, in contrast, participants were restricted in how they could move items off of the stack. When an item was selected, a red dot would appear in a random empty location in the grid at the top of the display (Figure 2.24). Participants were required to place the item in that spot, and failing to do so resulted in the item returning to its original position in the heap. The target item for each trial could either be moved to its designated location in the grid, or be moved directly to the response box to terminate the trial. In both conditions, participants were instructed to locate the target item and move it directly to the response box to terminate the trial. The next search trial commenced after a 250 ms delay.

Participants performed 1 practice trial in each condition, followed by 120 experimental trials. Experimental condition (Normal vs Forced) was blocked, with each participant completing 60 trials of Normal unpacking and 60 trials of Forced Deposit unpacking. The order of these blocks was counterbalanced across participants. The initial configuration of the items, as well as the grab time, drop time, and drop coordinates of each moved item were recorded.

Apparatus. The experiment was written and executed in Python using the pygame module, and run on an Apple mini, with OS X 10.6.4 and a 2.4GHz Intel Core 2 Duo processor. The stimulus displays were presented on a 24" Philips 244E2SB monitor at a resolution of 1920 by 1080, at a distance of 55 cm.

Results

Response Times and Number of Moves. As in the previous experiment, both Response Times (RTs) and the number of moves required during search were highly skewed. Both measures were adjusted

using a log transform; the values plotted and analyzed are based on the anti-logs of the mean log RTs / Number of Moves for each subject. The data are plotted in Figure 2.25, with Response Times plotted in panel A, and Number of Moves plotted in panel B.

Each measure was analyzed with a one-factor repeated measures ANOVA, with experimental condition (Normal, Forced) as the factor. Search in the Forced condition took longer, $F(1, 23) = 62.4$, $MSE = 3.513$, $p < .001$, and involved fewer moves, $F(1, 23) = 20.0$, $MSE = 1.354$, $p < .001$, as compared to search in the Normal condition. These results clearly validate the manipulation of movement speed, showing that not only did participants take longer overall during Forced search, but that they did so taking fewer moves – i.e., each individual move was substantially slowed for Forced search versus Normal unpacking.

Unpacking Errors. Error rates are plotted in Figure 2.26, and were analyzed with a Condition (Standard, Forced Deposit) by Error Type (Caught, Uncaught) repeated measures ANOVA. A marginal effect of Error Type was found, suggesting that Uncaught errors were slightly more prevalent than Caught errors, $F(1, 23) = 4.20$, $MSE = 20.120$, $p = .052$. Most critically however, there was a significant main effect of Condition, such that fewer errors occurred in the Forced condition, $F(1, 23) = 32.8$, $MSE = 36.069$, $p < .001$. The interaction was not significant ($F = 2.5$, $p = .128$). Coupled with the Response Time and Number of Moves data, these results confirm that when participants are induced to be slower and more considered in their movements during the unpacking task, the rate of the unpacking error is markedly decreased.

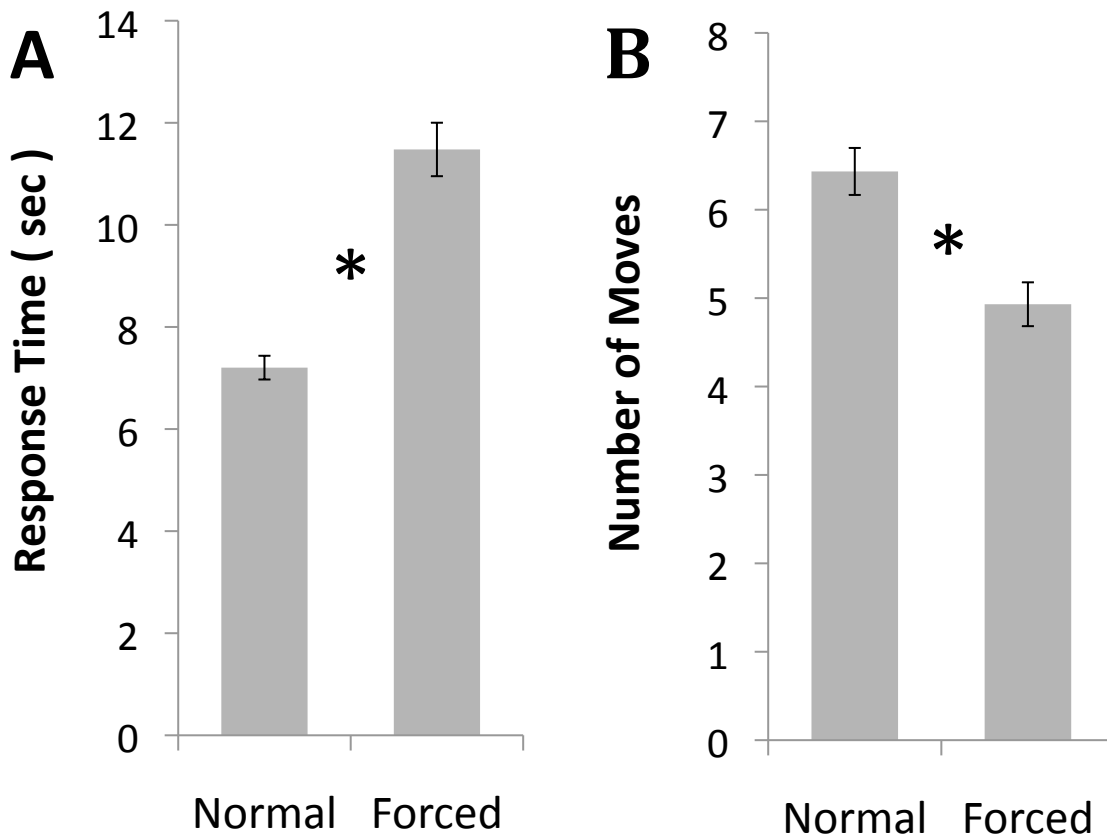


Figure 2.25 (A) Response Times (seconds) and (B) Number of moves per trial for Experiment 7, plotted for Normal and Forced Deposit condition. Error bars depict one standard error of the mean. * $p < .001$.

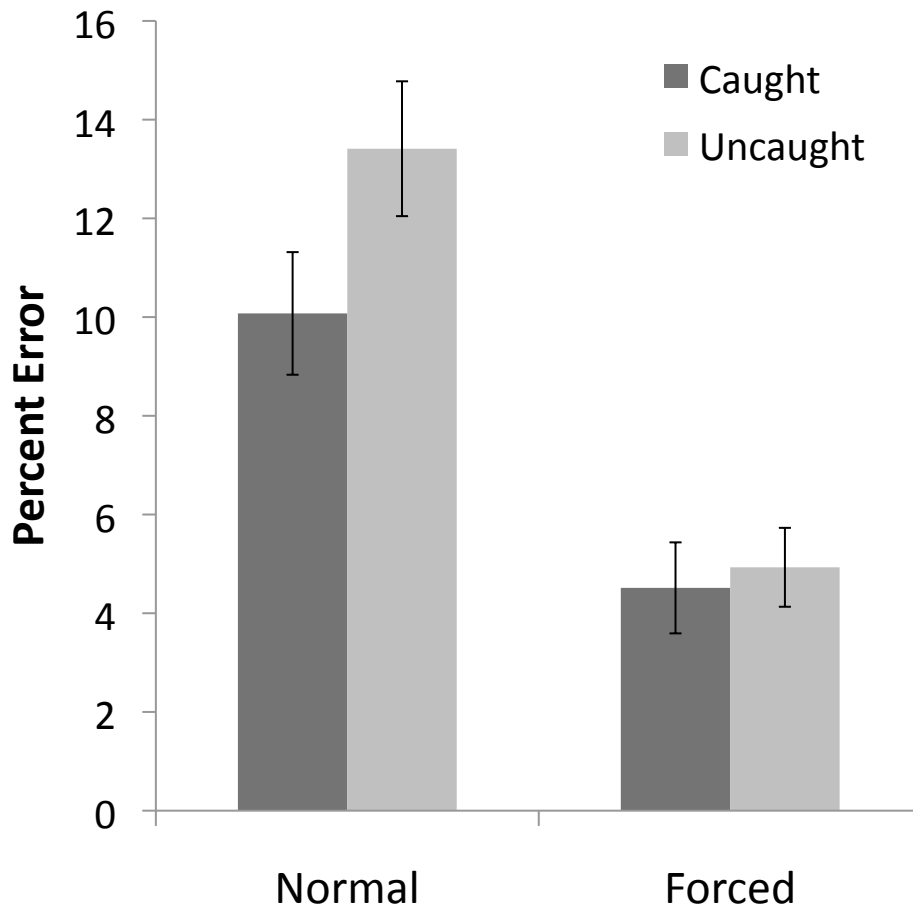


Figure 2.26 Caught and Uncaught error rates in Experiment 7, plotted for Normal and Forced Deposit conditions. Error bars depict one standard error of the mean.

Discussion

In the preceding experiments, participant behaviour on the Unpacking task indicated that the unpacking error is likely to result from excessive motor speeding, so that items are being selected and moved at a rate that outpaces the perceptual analysis necessary for reliable identification of those items. In Experiment 7, we provided a direct test of this hypothesis by forcing participants to slow down their movements through the structure of the task. As predicted by the motor-speeding hypothesis for the unpacking error, when participants were made to slow down, they likewise committed fewer unpacking errors.

2.8 Error Rates and Set Size: Meta-analysis

Although error rates were rarely found to be significantly impacted by set size in any given experimental sample, there is a clear trend across experiments for a small effect of set size. In the interests of completeness, we provide a brief meta-analysis of error rates collected across matched conditions in each of the experiments. The full sample included the Similar item set trials from Experiment 1 ($n = 16$), the No Load trials from Experiment 2 ($n = 28$), the Full-Vision trials from Experiment 3 ($n = 20$), all trials from Experiment 4 ($n = 20$) and Experiment 5 ($n = 30$), and the Mouse trials under standard instructions from Experiment 6 ($n = 20$), yielding a total sample of 134 participants. The data were entered into an Error Type (Caught, Uncaught) by Set Size (12, 24), by Experiment (1, 2, 3, 4, 5, 6) mixed factors ANOVA. A significant effect of Experiment was observed, $F(5, 128) = 3.06$, $MSE = 76.894$, $p < .05$, but Experiment did not interact with any other variables (largest $F = 1.39$, $ps = .233$) so we do not interpret this result further. We also note a small effect of Error Type, $F(1, 128) = 4.08$, $MSE = 44.275$, $p < .05$, such that Uncaught errors were slightly more prevalent. Critically, a significant effect of Set Size was found, $F(1, 128) = 13.6$, $MSE = 13.112$, $p < .001$. The effect was further examined by conducting a paired-samples t-test between Set Size 12 and Set Size 24 for each error type separately. We found no difference between Set Sizes for Caught errors ($t(133) = 1.130$, $p = .260$), but a significant difference between Set Sizes for Uncaught errors, $t(133) = 3.686$, $p < .001$. Although measurable with sufficient power, we note that the effect constitutes a negligible difference of approximately 1.5%, or just over a tenth of a percent per item.

3. General Discussion

A core component of search in the real world involves physical interaction with, and reconfiguration of critical elements of the search environment – including candidate targets. Here, we have introduced a novel search paradigm, the ‘Unpacking task,’ which includes these components of naturalistic search. The logical expectation for search of this type would hold that items should be consistently evaluated as candidate targets prior to being rejected. In contrast, we observed that participants frequently discard the target item during search, despite visually fixating and manipulating this target item, and despite the fact that locating the target is their exclusive task in most experiments. In seven experiments, we have attempted to elucidate the nature and characteristics of this error. In the following, we first propose an account for the unpacking error consistent with the data presented, then discuss the relation between the unpacking error and other common behavioral errors, and finally provide some concluding comments.

3.1 The Unpacking Error

Locating a target item in the Unpacking task involves the use of two distinct processes, by now quite familiar to psychologists: perception for identification, and perception for action (Goodale & Milner, 1992; Jeannerod, 1994). In the present context, the former (hereafter simply the ‘identification’ system) is responsible for determining the identity of a given item, or more generally, for determining whether or not the target item is present/visible in the display. The latter process (hereafter the ‘action’ system) is responsible for rearranging items in the display in order to uncover occluded items, thus making them accessible to the identification process. Implicit, and intuitively appealing in this description, is that, in the context of manual search, the action system should be slaved to the identification system. At times, however, the action system appears to be unresponsive to the identification system or, alternatively, the identification systems fails to assert sufficient control over

the action system. In either case, the action system appears to be decoupled from the identification system and hence from the core demand of the search task: to locate the sole target item, and is instead slaved to the more general aim of simply unpacking the heap – removing occlusion in order to ensure that any given item could in principle be inspected. This kind of dissociation is consistent with the idea that instantaneous visual processing is strongly tailored to immediate task demands (Ballard, Hayhoe, & Pelz, 1995; Hayhoe, Bensinger, & Ballard, 1998; Hoffman, Landau, & Pagani, 2003). When an item is selected for movement, it is not necessary that the item also be identified – its spatial coordinates are sufficient to support the motor program.

Such a division of labor may have interesting consequences, in particular when there is a discrepancy between the speed of processing for action and for identification. There appear to be two crucial thresholds in the relative timing of identification and action. First, if identification of an item completes prior to the onset of action, then the unpacking error will be avoided. Conversely, should identification fail to complete prior to movement onset, then the relative pace of ongoing identity analysis and subsequent movements will determine the severity of the error. If identification of the moved item completes prior to disruption by subsequent items, then the error will be caught, or else will have only minimal consequences. Conversely, if identification of the moved item is disrupted by subsequent item processing prior to completion, then the error is likely to be highly consequential. This hypothesis is supported, in particular, by Experiments 1, 3, and 7. When item identities can be quickly processed, as with the Dissimilar item set in Experiment 1, then the rate of consequential errors is low. Likewise, for Similar item sets – where identity processing is slower – reducing the level of distracting perceptual information in the display, as in the Yoked-vision condition in Experiment 3, leaves the *rate* of consequential errors unaffected, but reduces the severity of these errors. In this case, the increased processing demands make it more likely that the first threshold is crossed, but the reduced interference helps to prevent the second threshold from being crossed.

Finally, in Experiment 7 the motor speed was slowed, increasing the time available for perception to complete prior to the first threshold – and consequently reducing error rates.

That such a dissociation can be observed in a naturalistic context – and is apparently *more* likely when the ecological validity of the task is improved (Experiment 6) – raises interesting possibilities about how these two systems may interact more generally, and about how goal-oriented planning may unfold in naturalistic settings. In particular, in the case of the unpacking task, we can conceive of several different plans to achieve the goal of locating a target item. The naïve, and obvious plan would be to inspect each item in turn, discarding it if it is not the target, and moving it to the response box if it is the target. Such a process would undoubtedly be successful, but is apparently deemed too time-consuming – regardless of whether instructions emphasize speed or emphasize slowing (Experiment 6). An alternative plan would be to allow the motor system to randomly⁵ permute through configurations of the environment at its own pace, leaving the perceptual system to evaluate the outcomes of these permutations. While such an approach introduces the possibility of errors – which may at times be highly consequential – it may nonetheless reduce the average expected search time. Indeed, the positive skew distribution in response times seen across all the experiments reported here supports such an approach, shifting the bulk of the distribution to faster response times at the cost of a small number of much longer response times when an error is made. The prevalence of such distributions in naturalistic observations (the well-known power law, for instance; see e.g., Van Orden, Holden, & Turvey, 2005) suggests that this kind of tradeoff may indeed be the rule, and not the exception when it comes to real world behaviours like foraging.

⁵ The suggestion that this process is truly ‘random’ is likely unfair to the motor system, but is intended only to illustrate the overall flavor of this alternate strategy. A more apt characterization might hold that this motor exploration is not random, but rather is merely unconstrained by information related to the broader goal.

3.2 Relation to Documented Errors

In the following, we examine how the unpacking error we have introduced is related to a number of previously documented behavioral errors. In particular, we examine the relation of the unpacking error to (1) inattention blindness, (2) change blindness, (3) ‘misses’ in classical visual search, and (4) action slips in routine behavior.

Inattentional Blindness. When attention is focused on a particular location, feature, or component of a task, unexpected events occurring outside of this focus often go unnoticed – a phenomenon referred to as inattention blindness (Becklen & Cervone, 1983; Mack & Rock, 1998; Neisser & Becklen, 1975; Simons & Chabris, 1999). As in the inattention blindness paradigm, the unpacking task involves two processes, perception and action, which might potentially vie for attention and consequently interfere with one another. There are several reasons to doubt such an assessment. First, while most inattention blindness effects involve missing an unexpected and peripherally relevant event, it is difficult to argue that the target in the unpacking task – the primary and exclusive goal of the task – falls under the same category. It seems reasonable to differentiate failing to notice something unexpected and irrelevant, and failing to notice the object of an explicit, targeted search. Secondly, we note that the characteristics of the motor system’s behavior do not suggest an attentive focus on this process, but instead involve rapid, largely untargeted movements, typically without attendant eye-movements. Such seemingly automatic behavior is inconsistent with attentive focus. Indeed, we argue that the error is less likely to be a result of attending to the action process instead of the inspection process, and more likely a result of not attending to the action process enough, allowing this system to outpace the more demanding inspection process. Consequently, though one might reasonably make a case for ‘inattentional impulsivity,’ an inattention blindness account seems unlikely. Finally, we note that while inattention blindness has been found to increase under

conditions of memory load (Fougnie & Marois, 2007; Todd, Fougnie, & Marois, 2005), we found no such effects for the unpacking error.

Change Blindness. It has also been shown that individuals are surprisingly poor at identifying unexpected changes in the visual array, provided abrupt onset signals are masked, even for apparently quite dramatic changes (Droll, Hayhoe, Triesch, & Sullivan, 2005; McConkie & Zola, 1979; Levin & Simons, 1997; O'Regan, Rensik, & Clark, 1999). While demonstrations of change blindness clearly highlight the limitations of our perceptual abilities, there is little reason to believe that the present results arise from a common mechanism. As with inattention blindness, but not with the unpacking error, change blindness also increases as distraction increases (Smilek, Eastwood & Merikle, 2000). More critically, the unpacking error occurs under continuous viewing conditions, and, most importantly, in the absence of any change to the stimulus. The most immediately relevant demonstration of change blindness is found in Droll, Hayhoe, Triesch, & Sullivan (2005). These authors recorded hand and eye-movements during a virtual reality block sorting task, and reported the remarkable finding that changes could be made (during a period of saccadic suppression) to an item in hand without participants noticing, so that an item would be sorted on the basis of the characteristics it had when it was first selected, and not on the basis of its unexpectedly updated features. This result provides important insights into the nature of visual representations and visual working memory during movement, indicating that the representation of an item's identity is not necessarily updated after it has been used for selection. Critically however, during the unpacking error the motor behavior is enacted *before* identification, and consequently is not a failure to update the representation, but a failure to acquire one in the first place.

Visual Search Misses. The Unpacking task incorporates a motor component into the traditional visual search paradigm, introducing the dimension of depth and the consequent potential for occlusion of the target, thereby requiring introduction of a motor component to the search repertoire –

conceptually analogous to the factor of eccentricity, which necessitates visual orienting actions (e.g. eye-movements). Consequently, it is important to explore the relation between the unpacking error and errors observed in traditional visual search. In particular, it has been reliably demonstrated that during visual search tasks in which the target is sometimes present and sometimes absent, participants will often ‘miss’ the target item, responding that it is absent even when it was in fact present, and the rate of this error typically increases as target prevalence decreases (Rich et al., 2008; Van Wert, Horowitz, & Wolfe, 2009; Wolfe, Horowitz, Kenner, 2005; Wolfe et al., 2007; but see Fleck & Mitroff, 2007). We acknowledge that errors of this type are closely related to the unpacking error, but highlight several important caveats for such a comparison.

First, we note that Rich and colleagues (2008) have demonstrated with eye-tracking data that the bulk of miss errors occur on trials where the target item was not fixated in the course of search – indicating that, in the majority of cases, target misses arise because search was terminated prematurely, not because participants failed to identify an inspected item. In contrast, we have shown that the target is typically fixated for approximately 300 ms prior to an unpacking error, and that this level of inspection differs only marginally from the amount of inspection prior to correct target detection. Notably, there is also a minority of target misses during visual search for which the target item was in fact fixated, and these errors are certainly more closely related to the unpacking error. However, even in the case of these more similar errors, we note that the motor component in the unpacking task introduces a compounding factor in the severity of the error by imposing an external time limit on inspection. It would be interesting to investigate whether the rate of eye-movements during traditional visual search might also show a tendency to outpace the rate of identification processes.

Second, it is important to note that in the experiments presented here, the target was present on *every* trial, corresponding to a 100% prevalence rate. This presents a fundamental contrast to studies

of visual search misses, where by necessity the target must be absent on some of the trials in order to measure misses. In these studies, a high prevalence condition is typically one where the target is present on 50% of trials, while a low prevalence condition generally has a target present on only 1%-5% of trials. Misses occur in both conditions, but are particularly common in the low prevalence case. These errors have been explained using the ‘multiple-decision model,’ which proposes that search responses are influenced by a response criterion, which biases evaluation of target-presence in the attended region of the search array, and a quitting threshold that governs when searchers decide to stop looking and respond that the target is absent (Wolfe & Van Wert, 2010). In particular, under conditions of low target prevalence searchers are thought to become biased toward ‘absent’ responses locally, and likewise reduce their quitting threshold, giving up more quickly. Under high prevalence conditions, these effects are reversed, so that local inspection is biased toward ‘present’ responses, and the quitting threshold is increased. Given the 100% target prevalence rate in the Unpacking task, the multiple-decision model – which successfully explains visual search misses – appears ill-suited to explain the unpacking error.

Action Slips. Finally, the unpacking error also seems reminiscent of action slips in routine behaviour (e.g. Botvinick & Plaut, 2004; Cooper & Shallice, 2000; Norman, 1981; Reason, 1979; Wagenaar, Hudson, & Reason, 1990; Zapf & Reason, 1994). In particular, we note that the unpacking error appears to result from a failure to adequately control the action system – and in particular a failure to maintain task-appropriate contingencies between action and identification. Such an account raises an interesting possibility for models of behavioral control. Specifically, we suggest that subgoaling is not necessarily a matter of decomposing a task into a linear set of sub-goals, but rather that tasks may sometimes be partitioned into temporally overlapping sub-tasks carried out by dissociable systems. In the present case, the unpacking task is partitioned into two main sub-components: unpacking, and inspecting. These two components can be carried out by separable

systems, and consequently operate heterarchically (Norman, 1981) – leading to errors of discoordination when the two systems fail to share critical information, or fail to adequately cross-regulate. Consistent with such an account is the observation of post-error slowing in the unpacking task, indicating some rudimentary awareness of the error, and a consequent attempt to increase control over the action system.

3.3 Concluding Comments

In the present research, we have extended the classical visual search paradigm to include a more active exploratory component by having participants search through a heap of items. In so doing, we discovered that the most obvious and intuitive strategic approach to search – identifying an item before choosing how to act on it (i.e., whether to discard it, or accept it as the target) – is not necessarily the strategy that is typically used. Instead, the search process as a whole seems to be decomposed into a motor task (“make items available to inspection”), and a perceptual task (“determine whether or not the target is among those items available to inspection”). Critically, rather than coupling these processes, so that, for instance, only those items known to be non-targets are rejected by the motor system, it appears that the two processes are allowed to run concurrently, but largely without mutual control. As a consequence, the motor system at times outpaces the perceptual system, rejecting an item before it has been fully processed, and consequently before it can be determined whether or not that item is the target. While it has long been known that perception for action and perception for identification are dissociable (Goodale & Milner, 1992; Jeannerod, 1994), observations of this dissociation have typically involved either lesions to one system or the other (e.g., Carey, Harvey, & Milner, 1996; Goodale, Milner, Jakobson, & Carey, 1991; James, Culham, Humphrey, Milner, & Goodale, 2003; Milner, et al., 1991; Rice, et al., 2006), or the use of careful experimental designs that place the two systems in conflict, typically using visual illusions (e.g., Aglioti, DeSouza, & Goodale, 1995; Bruno, Bernardis, & Gentilucci, 2008; Haffenden & Goodale,

1998; Ganel, Tanzer, & Goodale, 2008; Goodale, 2008; Króliczak, Heard, Goodale, & Gregory, 2006). In contrast, the unpacking error appears to capture some aspect of this dissociation during a naturalistic task where the intuitive expectation would not only hold that the two systems should not be dissociated, but that they should in fact be fairly closely coupled.

Appendix A

Trace Computation – Experiment 3

Data was sampled throughout performance of the task. Because both sampling and stimulus display were handled by the same program, sampling times varied based on computational load. With no item selected, data was sampled at an average rate of once every 20.5 ms (48.6 Hz). When an item was selected, the rate decreased to an average of once every 33.3 ms (30.0 Hz). For each sample we recorded the mouse coordinates, the time that the sample was recorded, the identity of the item currently selected (if any), and the offset of the selection point on the item (if an item was selected). In conjunction with trial level specification of the starting state, and redundant recordings of coarse move characteristics (item, grab time, drop time, drop coordinates), these data allowed full reconstruction of the display's state at a rate of 30.0 – 48.6 Hz.

To extract task-relevant features from the movement data, each trial was first divided into segments falling into one of three categories: 1) mouse free segments – contiguous series of samples with no item selection, 2) standard move segments – contiguous series of samples with a non-target item selected, and 3) target move segments – contiguous series of samples with the target item selected. For each sample within a segment, we estimated the instantaneous velocity (in degrees per second) on the basis of that sample and the samples immediately preceding and following. Instantaneous velocity for the first and last samples within a trace was computed using only the single neighboring sample, and was divided by two to attenuate edge artifacts (equivalent to assuming the mouse is stationary before and after the segment).

$$v_n = \frac{(x_n - x_{n-1}) + (x_{n+1} - x_n)}{2}$$

For each sample within a segment, we also computed the vector from the sample coordinate to the center of the response box. We then determined the projection of the instantaneous velocity of the sample onto this response box vector – the component of the movement at that time that was directed

towards the response box. Because the response box had spatial extent, the projection was set to zero if the sample coordinate was within the bounds of the response box.

Average traces were computed across all matching segments across all trials for each subject. Each matching segment was sampled at 50 evenly spaced time points (the absolute spacing varied depending on the total duration of each segment). Temporal smoothing was applied by computing a weighted average at each time point of the instantaneous velocity and of the projection onto the response box vector across all samples in the segment, using a Gaussian kernel with a standard deviation of 30 ms. The values at each ordinal time point were averaged across segments for each subject, along with the average sampling time across segments.

Traces were computed separately for Correct trials (trials where the target item was moved only once – to the response box), Caught error trials (trials where the target item was moved twice, but without any intervening activity) and Uncaught error trials (trials where the target item was moved two or more times, with at least one move occurring between the first target move and the trial-terminating target move). All traces were computed separately for Visible and Yoked conditions.

Bibliography

- Acks, D. J., Zelinsky, G. J., & Sprott, J. C. (2002). Memory across eye-movements: 1/f Dynamic in visual search. *Nonlinear Dynamics, Psychology, & Life Sciences*, 6, 1-25.
- Aglioti, S., DeSouza, J. F. X., & Goodale, M. A. (1995). Size-contrast illusions deceive the eye but not the hand. *Current Biology*, 5, 679-685.
- Ambrosini, E., Sinigaglia, C., & Costantini, M. (2012). Tie my hands, tie my eyes. *Journal of Experimental Psychology: Human Perception and Performance*, 38, 263-266.
- Baldauf, D., & Deubel, H. (2008). Attentional selection of multiple goal positions before rapid hand movement sequences: An event-related potential study. *Journal of Cognitive Neuroscience*, 21, 18-29.
- Baldauf, D., & Deubel, H. (2010). Attentional landscapes in reaching and grasping. *Vision Research*, 50, 999-1013.
- Ballard, D. H., Hayhoe, M. M., & Pelz, J. B. (1995). Memory representations in natural tasks. *Journal of Cognitive Neuroscience*, 7, 66-80.
- Barnes, G. R. (1979). Vestibulo-ocular function during coordinated head and eye movements to acquire visual targets. *The Journal of Physiology*, 287, 127-147.
- Bassolino, M., Serino, A., Ubaldi, S., Ladavas, E. (2010). Everyday use of the computer mouse extends peripersonal space representation. *Neuropsychologia* 4, 803-811.
- Becklen, R., & Cervone, D. (1983). Selective looking and the noticing of unexpected events. *Memory & Cognition*, 11, 601-608.
- Berman, R., & Colby, C. (2009). Attention and active vision. *Vision Research*, 49, 1233-1248.
- Biederman, I., Mezzanotte, R. J., & Rabinowitz, J. C. (1982). Scene perception: Detecting and judging objects undergoing relational violations. *Cognitive Psychology*, 14, 143-177.
- Botvinich, M., & Plaut, D. C. (2004). Doing without schema hierarchies: A recurrent connectionist approach to normal and impaired routine sequential action. *Psychological Review*, 11, 395-429.

- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*, 443-446.
- Brockmole, J. R., Castelano, M. S., & Henderson, J. M. (2006). Contextual cueing in naturalistic scenes: Global and local contexts. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 32*, 699-706.
- Bruno, N., Bernardis, P., & Gentilucci, M. (2008). Visually guided pointing, the Müller-Lyer illusion, and the functional interpretation of the dorsal-ventral split: Conclusions from 33 independent studies. *Neuroscience and Biobehavioral Reviews, 32*, 423-437.
- Carey, D. P., Harvey, M., & Milner, A. D. (1996). Visuomotor sensitivity for shape and orientation in a patient with visual form agnosia. *Neuropsychologia, 34*, 329-337.
- Carrasco, M., & McElree, B. (2001). Covert attention accelerates the rate of visual information processing. *Proceedings of the National Academy of Sciences, 98*, 5363-5367.
- Chen, X., & Zelinsky, G. J. (2006). Real-world visual search is dominated by top-down guidance. *Vision Research, 46*, 4118-4133.
- Chun, M.M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36*, 28-71.
- Chun, M.M., & Jiang, Y. (1999). Top-down attentional guidance based on implicit learning of visual covariation. *Psychological Science, 10*, 360-365.
- Cisek, P. (2007). Cortical mechanisms of action selection: the affordance competition hypothesis. *Philosophical Transactions of the Royal Society B, 362*, 1585-1599.
- Cisek, P., & Kalaska, J. F. (2010). Neural mechanisms for interacting with a world full of action choices. *Annual Review of Neuroscience, 33*, 269-298.
- Cooper, R., & Shallice, T. (2000). Contention scheduling and the control of routine activities. *Cognitive Neuropsychology, 17*, 297-338.

- De Graef, P., Christiaens, D., & d'Ydewalle, G. (1990). Perceptual effects of scene context on object identification. *Psychological Research, 52*, 317-329.
- Dickinson, C. A., & Zelinsky, G. J. (2007). Memory for the search path: Evidence for a high-capacity representation of search history. *Vision Research, 47*, 1745-1755.
- Droll, J. A., Hayhoe, M. M., Triesch, J., & Sullivan, B. T. (2005). Task demands control acquisition and storage of visual information. *Journal of Experimental Psychology: Human Perception & Performance, 31*, 1416-1438.
- Duncan, J., & Humphreys, G. W. (1989). Visual search and stimulus similarity. *Psychological Review, 96*, 433-458.
- Eckstein, M. P., Drescher, B. A., & Shimozaki, S. S. (2006). Attentional cues in real scenes, saccadic targeting, and Bayesian priors. *Psychological Science, 17*, 973-980.
- Endo, N., & Takeda, Y. (2005). Use of spatial context is restricted by relative position in implicit learning. *Psychonomic Bulletin & Review, 12*, 880-885.
- Evans, K. K., Cohen, M. A., Tambouret, R., Horowitz, T., Kreindel, E., & Wolfe, J. M. (2011). Does visual expertise improve visual recognition memory? *Attention, Perception, & Psychophysics, 73*, 30-35.
- Fleck, M. S., & Mitroff, S. R. (2007). Rare targets are rarely missed in correctable search. *Psychological Science, 18*, 943-947.
- Findlay, J., & Gilchrist, I. D. (2003). *Active Vision: The psychology of looking and seeing.* (pp. 14-15). New York, Oxford University Press Inc.
- Fougnie, D., & Marois, R. (2007). Executive working memory load induces inattention blindness. *Psychonomic Bulletin & Review, 14*, 142-147.
- Freeman, J. B., Dale, R., & Farmer, T. A. (2011). Hand in motion reveals mind in motion. *Frontiers in Psychology, 2*, 1-6.

- Ganel, T., Tanzer, M., & Goodale, M. A. (2008). A double dissociation between action and perception in the context of visual illusions. *Psychological Science, 19*, 221-225.
- Geng, J. J., & Behrmann, M. (2005). Spatial probability as an attentional cue in visual search. *Perception & Psychophysics, 67*, 1252-1268.
- Gilchrist, I. D., & Harvey, M. (2000). Refixation frequency and memory mechanisms in visual search. *Current Biology, 10*, 1209-1212.
- Goldenberg, G., & Iriki, A. (2007). From sticks to coffemaker: Mastery of tools and technology by human and non-human primates. *Cortex, 43*, 285-288.
- Goodale, M. A. (2008). Action without perception in human vision. *Cognitive Neuropsychology, 25*, 891-919.
- Goodale, M. A., & Milner, A. D. (1992). Separate visual pathways for perception and action. *Trends in Neuroscience, 15*, 20-25.
- Goodale, M. A., Milner, A. D., Jakobson, L. S., & Carey, D. P. (1991). A neurological dissociation between perceiving objects and grasping them. *Nature, 349*, 154-156.
- Goolsby, B. A., & Suzuki, S. (2001). Understanding priming of color-singleton search: Roles of attention at encoding and "retrieval". *Perception & Psychophysics, 63*, 929-944.
- Gordon, G., Kaplan, D. M., Lankow, B., Little, D. Y., Sherwin, J., Suter, B. A., & Thaler, L. (2011). Toward an integrated approach to perception and action: conference report and future directions. *Frontiers in Systems Neuroscience, 5*, 1-6.
- Gottlieb, J. (2007). From thought to action: The parietal cortex as a bridge between perception, action, and cognition. *Neuron, 53*, 9-16.
- Haffenden, A. M., & Goodale, M. A. (1998). The effect of pictorial illusion on prehension and perception. *Journal of Cognitive Neuroscience, 10*, 122-136.

- Hannus, A., Cornelissen, F. W., Lindemann, O., & Bekkering, H. (2005). Selection-for-action in visual search. *Acta Psychologica, 118*, 171-191.
- Hatsopoulos, N. G., & Suminski, A. J. (2011). Sensing with the motor cortex. *Neuron, 72*, 477-487.
- Hayhoe, M. M., Bensinger, D. G., & Ballard, D. H. (1998). Task constraints in visual working memory. *Vision Research, 38*, 125-137.
- Henderson, J. M., Brockmole, J. R., Castelhana, M. S., & Mack, M. (2007). Visual saliency does not account for eye movements during visual search in real-world scenes. In: R. P. G. van Gompel, M. H. Fischer, W. S. Murray, & R. L. Hill (Eds.), *Eye Movements: A Window on Mind and Brain* (pp. 537-562). Oxford: Elsevier.
- Hester, R., Foxe, J. J., Molholm, S., Shpaner, M. & Garavan, H. (2005) Neural mechanisms involved in error processing: a comparison of errors made with and without awareness. *Neuroimage, 27*, 602–608.
- Hester, R., Simões-Franklin, C., & Garavan, H. (2007) Post-error behaviour in active cocaine users: Poor awareness of errors in the presence of intact performance adjustments. *Neuropsychopharmacology, 32*, 1974–1984.
- Hillstrom, A. P. (2000). Repetition effects in visual search. *Perception & Psychophysics, 62*, 800-817.
- Hoffman, J. E., Landau, B., & Pagani, B. (2003). Spatial breakdown in spatial construction: Evidence from eye fixations in children with Williams syndrome. *Cognitive Psychology, 46*, 260-301.
- Hollingworth, A. & Henderson, J. M. (1998) Does consistent scene context facilitate object perception? *Journal of Experimental Psychology: General, 127*, 398-415.
- Hooge, I. T., & Erkelens, C. J. (1999). Peripheral vision and oculomotor control during visual search. *Vision Research, 39*, 1567-1575.

- Howard, C. J., Pharaon, R. G., Körner, C., Smith, A. D., & Gilchrist, I. D. (2011) Visual search in the real world: Evidence for the formation of distractor representations. *Perception, 40*, 1143-1153.
- Horowitz, T. S. (1995). Distractor inhibition in a visual search task. *Investigative Ophthalmology and Visual Science, 36*, 4126.
- Horowitz, T. S., & Wolfe, J. M. (1998). Visual search has no memory. *Nature, 394*, 575-577.
- Horowitz, T. S., & Wolfe, J. M. (2003). Memory for rejected distractors in visual search? *Visual Cognition, 10*, 257-298.
- Hunt, A. R., & Kingstone, A. (2003). Covert and overt voluntary attention: linked or independent? *Cognitive Brain Research, 18*, 102-105.
- Itti, L., & Koch, C. (2000). A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Research, 40*, 1489-1506.
- James, T. W., Culham, J., Humphrey, G. K., Milner, A. D., & Goodale, M. A. (2003). Ventral occipital lesions impair object recognition but not object-direction grasping: an fMRI study. *Brain, 126*, 2463-2475.
- Jeannerod, M. (1994). The representing brain: Neural correlates of motor intention and imagery. *Behavioral and Brain Sciences, 17*, 187-202.
- Jiang, Y., & Leung, A. W. (2005). Implicit learning of ignored visual context. *Psychonomic Bulletin & Review, 12*, 100-106.
- Jiang, Y., & Song, J.-H. (2005). Hyperspecificity in visual implicit learning: Learning of spatial layout is contingent on item identity. *Journal of Experimental Psychology: Human Perception and Performance, 31*, 1439-1448.
- Körner, C., & Gilchrist, I. D. (2007). Finding a new target in an old display: Evidence for a memory recency effect in visual search. *Psychonomic Bulletin & Review, 14*, 846-851.

- Kristjánsson, À. (2000). In search of remembrance: Evidence for memory in visual search. *Psychological Science, 11*, 328-332.
- Króliczak, G., Heard, P., Goodale, M. A., & Gregory, R. L. (2006). Dissociation of perception and action unmasked by the hollow-face illusion. *Brain Research, 1080*, 9-16.
- Kumada, T., & Humphreys, G. W. (2002). Cross-dimensional interference and cross-trial inhibition. *Perception & Psychophysics, 64*, 493-503.
- Kunar, M. A., Flusberg, S., & Wolfe, J. M. (2008). The role of memory in restricted context in repeated search. *Perception & Psychophysics, 70*, 314-328.
- Kunar, M. A., & Watson, D. G. (2011). Visual search in a multi-element asynchronous dynamic (MAD) world. *Journal of Experimental Psychology: Human Perception and Performance, 37*, 1017-1031.
- Leonards, U., Rettenbach, R., Nase, G., & Sireteanu, R. (2002). Perceptual learning of highly demanding visual search tasks. *Vision Research, 42*, 2193-2204.
- Levin, D. T., & Simons, D. J. (1997). Failure to detect changes to attended objects in motion pictures. *Psychonomic Bulletin & Review, 4*, 501-506.
- Lewicki, P., Czyzewska, M., & Hoffman, H. (1987). Unconscious acquisition of complex procedural knowledge. *Journal of Experimental Psychology: Learning, Memory, & Cognition, 13*, 523-530.
- Mack, A., & Rock, I. (1998). *Inattentional Blindness*. MIT Press.
- Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory and Cognition, 22*, 657-672.
- Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. Role of position. *Perception & Psychophysics, 58*, 977-991.
- Maljkovic, V., & Nakayama, K. (2000). Priming of pop-out: III. A short-term implicit memory system beneficial for rapid target selection. *Visual Cognition, 7*, 571-595.

- McCarley, J. S., Wang, R. F., Kramer, A. F., Irwin, D. E., & Peterson, M. S. (2003). How much memory does oculomotor search have? *Psychological Science, 14*, 422-426.
- McConkie, G. W., & Zola, D. (1979). Is visual information integrated across successive fixations in reading?. *Perception & Psychophysics, 25*, 221-224.
- McPeck, R. M., Maljkovic, V., & Nakayama, K. (1999). Saccades requires focal attention and are facilitated by a short-term memory system. *Vision Research, 39*, 1555-1566.
- Miller, J. (1988). Components of the location probability effect in visual search tasks. *Journal of Experimental Psychology: Human Perception & Performance, 14*, 453-471.
- Milner, A. D., Perrett, D. I., Johnston, R. S., Benson, P. J., Jordan, T. R., Heeley, D. W., Bettucci, D., Mortara, F., Mutani, R., Terazzi, E., & Davidson, D. L. W. (1991). Perception and action in 'visual form agnosia'. *Brain, 114*, 405-428.
- Motter, B. C., & Holsapple, J. (2007). Saccades and covert shifts of attention during active visual search: Spatial distributions, memory, and items per fixations. *Vision Research, 47*, 1261-1281.
- Najemnik, J., & Geisler, W. S. (2005). Optimal eye movement strategies in visual search. *Nature, 434*, 387-391.
- Neider, M. B., & Zelinsky, G. J. (2006). Scene context guides eye movements during visual search. *Vision Research, 46*, 614-621.
- Neisser, U. (1976). *Cognition and Reality: Principles and implications of cognitive psychology*. W. H. Freeman and Company.
- Neisser, U., & Becklen, R. (1975). Selective looking: Attending to visually specified events. *Cognitive Psychology, 7*, 480-494.
- Nii, Y., Uematsu, S., Lesser, R. P., & Gordon, B. (1996). Does the central sulcus divide motor and sensory functions? *Neurology, 46*, 360-367.
- Norman, D. A. (1981). Categorization of action slips. *Psychological Review, 88*, 1-15.

- Pelli, D. G. (1997) The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10*, 437-442.
- Olivia, A., Wolfe, J. M., & Arsenio, H. C. (2004). Panoramic search: The interaction of memory and vision in search through a familiar scene. *Journal of Experimental Psychology: Human Perception and Performance, 30*, 1132-1146.
- Olson, I.R., & Chun, M.M. (2002). Perceptual constraints on implicit learning of spatial context. *Visual Cognition, 9*, 273-302.
- O'Regan, J. K., Rensink, R. A., & Clark, J. J. (1999). Change-blindness as a result of 'mudsplashes'. *Nature, 398*, 34.
- Peterson, M. S., Beck, M. R., & Vomela, M. (2007). Visual search is guided by prospective and retrospective memory. *Perception & Psychophysics, 69*, 123-135.
- Peterson, M. S., Kramer, A. F., Wang, R. F., Irwin, D. E., & McCarley, J. S. (2001). Visual search has memory. *Psychological Science, 12*, 287-292.
- Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32*, 3-25.
- Rabbitt, P. (2002). Consciousness is slower than you think. *The Quarterly Journal of Experimental Psychology, 55A*, 1081-1092.
- Rao, R. P. N., Zelinsky, G. J., Hayhoe, M. M., & Ballard, D. H. (2002). Eye movements in iconic visual search. *Vision Research, 42*, 1447-1463.
- Reason, J. T. (1979). Actions not as planned: The price of automatization. In Underwood, G., & Stevens, R., (Eds), *Aspects of Consciousness*, (Ch. 4, pp. 515-549). Academic Press.
- Reichle, E. D., Reineberg, A. E., & Schooler, J. W. (2010). Eye movements during mindless reading. *Psychological Science, 21*, 1300-1310.

- Rice, N. J., McIntosh, R. D., Schindler, I., Mon-Williams, M., Démonet, J., & Milner, A. D. (2006). Intact automatic avoidance of obstacles in patients with visual form agnosia. *Experimental Brain Research, 174*, 176-188.
- Rich, A. N., Kunar, M. A., Van Wert, M. J., Hidalgo-Sotelo, B., Horowitz, T. S., & Wolfe, J. M. (2008). Why do we miss rare targets? Exploring the boundaries of the low prevalence effect. *Journal of Vision, 8*, 1-17.
- Robinson, G. H., Koth, B. W., & Ringenbach, J. P. (1976). Dynamics of the eye and head during an element of visual search. *Ergonomics, 19*, 691-709.
- Rosenbaum, D. A. (2005). The Cinderella of psychology: The neglect of motor control in the science of mental life and behavior. *American Psychologist, 60*, 308-317.
- Shore, D. I., & Klein, R. M. (2000). On the manifestations of memory in visual search. *Spatial Vision, 14*, 59-75.
- Simons, D. J., & Chabris, C. F. (1999). Gorillas in our midst: Sustained inattention blindness for dynamic events. *Perception, 28*, 1059-1074.
- Sireteanu, R., & Rettenbach, R. (1995). Perceptual learning in visual search: Fast, enduring, but non-specific. *Vision Research, 35*, 2037-2043.
- Smilek, D., Eastwood, J.D., & Merikle, P.M. (2000). Does unattended information facilitate change detection? *Journal of Experimental Psychology: Human Perception and Performance, 26*, 480-487.
- Smilek D., Frischen, A., Reynolds, M. G., Gerritson, C., & Eastwood, J. D. (2007). What influences visual search efficiency? Disentangling contributions of preattentive and postattentive processes. *Perception & Psychophysics, 69*, 1105-1116.
- Smith, A. D., Hood, B. M., & Gilchrist, I. D. (2008). Visual search and foraging compared in a large-scale search task. *Cognitive Processing, 9*, 121-126.

- Smith, A. D., Hood, B. M., & Gilchrist, I. D. (2010). Probabilistic cueing in large-scale environmental search. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *36*, 605-618.
- Smith, A. D., Wallace, F., Hood, B., & Gilchrist, I. D. (2009). Mechanisms of large-scale environmental search: probability cueing depends on the relationship between landmarks and target distribution. *Cognitive Processing*, *10*, S305-S306.
- Solman, G. J. F., Cheyne, J. A., & Smilek, D. (2011). Memory load affects visual search processes without influencing search efficiency. *Vision Research*, *51*, 1185-1191.
- Solman, G. J. F., Cheyne, J. A., & Smilek, D. (In Press). A change in perspective: Zooming in and out during visual search. *Journal of Experimental Psychology: Human Perception and Performance*: 2012-0616-RR.
- Solman, G. J. F., & Smilek, D. (2010). Item-specific memory in visual search. *Vision Research*, *50*, 2430-2438.
- Solman, G. J. F., & Smilek, D. (2012). Memory benefits during visual search depend on difficulty. *Journal of Cognitive Psychology*, doi:10.1080/20445911.2012.682053.
- Summala, H., Pasanen, E., Räsänen, M., & Sievänen, J. (1996). Bicycle accidents and drivers' visual search at left and right turns. *Accidental Analysis & Prevention*, *28*, 147-153.
- Thomas, L. E., Ambinder, M. S., Hsieh, B., Levinthal, B., Crowell, J. A., Irwin, D. E., Kramer, A. F., Lleras, A., Simons, D. J., & Wang, R. F. (2006). Fruitful visual search: Inhibition of return in a virtual foraging task. *Psychonomic Bulletin & Review*, *13*, 891-895.
- Todd, J. J., Fougnie, D., & Marois, R. (2005). Visual short-term memory load suppresses temporo-parietal junction activity and induces inattention blindness. *Psychological Science*, *16*, 965-972.
- Torrallba, A., Oliva, A., Castelhana, M., & Henderson, J. M. (2006). Contextual guidance of attention in natural scenes: The role of global features on object search. *Psychological Review*, *113*, 766-786.

- Treisman, A., & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*, 97-136.
- Van Orden, G. C., Holden, J. G., & Turvey, M. T. (2005). Human cognition and 1/f scaling. *Journal of Experimental Psychology: General*, *134*, 117-123.
- Van Wert, M. J., Horowitz, T. S., & Wolfe, J. M. (2009). Even in correctable search, some types of rare targets are frequently missed. *Attention, Perception, & Psychophysics*, *71*, 541-553.
- Võ, M., & Wolfe, J. M. (2012). When does repeated search in scenes involve memory? Looking at versus looking for objects in scenes. *Journal of Experimental Psychology: Human Perception and Performance*, *38*, 23-41.
- Wagenaar, W. A., Hudson, P. T. W., & Reason, J. T. (1990). Cognitive failures and accidents. *Applied Cognitive Psychology*, *4*, 273-294.
- Williams, C. C., Henderson, J. M., & Zacks, R. T. (2005). Incidental visual memory for targets and distractors in visual search. *Perception & Psychophysics*, *67*, 816-827.
- Williams, C. C., Pollatsek, A., Cave, K. R., & Stroud, M. J. (2009). More than just finding color: Strategy in global visual search is shaped by learned target probabilities. *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 688-699.
- Wolfe, J. M. (1994). Guided search 2.0: A revised model of visual search. *Psychonomic Bulletin & Review*, *1*, 202-238.
- Wolfe, J. M. (1994). Visual search in continuous, naturalistic stimuli. *Vision Research*, *34*, 1187-1195.
- Wolfe, J. M. (2007). Guided search 4.0: Current progress with a model of visual search. In W. Gray (Ed.) *Integrated Models of Cognitive Systems* (pp. 99-119). New York: Oxford.
- Wolfe, J. M., Alvarez, G. A., Rosenholtz, R., Kuzmova, Y. I., & Sherman, A. M. (2011). Visual search for arbitrary objects in real scenes. *Attention, Perception, & Psychophysics*, *73*, 1650-1671.

- Wolfe, J. M., Horowitz, T. S., & Kenner, N. M. (2005). Rare items often missed in visual searches. *Nature*, *435*, 439-440.
- Wolfe, J. M., Horowitz, T. S., Van Wert, M. J., Kenner, N. M., Place, S. S., & Kibbi, N. (2007). Low target prevalence is a stubborn source of errors in visual search tasks. *Journal of Experimental Psychology: General*, *136*, 623-638.
- Wolfe, J. M., Klempe, N., & Dahlen, K. (2000). Postattentive vision. *Journal of Experimental Psychology: Human Perception and Performance*, *26*, 693-716.
- Wolfe, J. M., & Van Wert, M. J. (2010). Varying target prevalence reveals two dissociable decision criteria in visual search. *Current Biology*, *20*, 121-124.
- Woodman, G. F., Vogel, E. K., & Luck, S. J. (2001). Visual search remains efficient when visual working memory is full. *Psychological Science*, *12*, 219-224.
- Yarbus, A.I. (1967). *Eye movements and vision* (English trans. by L. A. Riggs), Plenum Press, New York.
- Zapf, D., & Reason, J. T. (1994). Introduction: Human errors and error handling. *Applied Psychology: An International Review*, *43*, 427-432.
- Zelinsky, G. J., Rao, R. P. N., Hayhoe, M. M., & Ballard, D. H. (1997). Eye movements reveal the spatiotemporal dynamics of visual search. *Psychological Science*, *8*, 448-453.