Top-down and bottom-up aspects of active search in a real world environment

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Abstract

Visual search has been studied intensively in the laboratory, but lab search often differs from search in the real world in many respects. Here, we used a mobile eye-tracker to record the gaze of participants engaged in a realistic, active search task. Participants were asked to walk into a mailroom and locate a target mailbox among many similar mailboxes. This procedure allowed control of bottom-up cues (by making the target mailbox more salient; Experiment 1) and top-down instructions (by informing participants about the cue; Experiment 2). The bottom-up salience of the target had no effect on the overall time taken to search for the target, although the salient target was more likely to be fixated and found once it was within the central visual field. Top-down knowledge of target appearance had a larger effect, reducing the need for multiple head and body movements, and meaning that the target was fixated earlier and from further away. Although there remains much to be discovered in complex real-world search, this study demonstrates that principles from visual search in the laboratory influence gaze in natural behaviour, and provides a bridge between these laboratory studies and research examining vision in natural tasks.

Introduction

Human visual attention has been studied extensively by asking participants to search for a target on a computer screen. When the target is dramatically different from the other items in the display then the target is easy to find, and thus the properties of the stimulus are believed to drive the attention of the observer. In a different but related line of work, investigations of gaze allocation in complex scenes have tended to focus on the fixations made when people look at static pictures. Much of this work tests the principle that image salience guides where people look, and thus visually distinctive or surprising locations are preferentially fixated.

In both search and scene viewing, therefore, the principle of feature-driven or bottom-up attentional selection has been derived from performance in the restricted conditions of computer-based experiments. The aim of the present research was to determine the extent to which this principle generalizes to gaze allocation in a real world search task. We begin by describing how visual search has been studied, both in the laboratory and in the context of a natural scene. We then outline some of the reasons why it is important to study the generalization of cognitive principles to natural behaviour, and consider the implications for visual search and gaze allocation.

Simple visual search in the lab

Visual search—the behaviours and mechanisms that allow us to find visual objects—is possibly the most investigated task in cognitive science. Over a decade ago, more than a million trials had been analysed and thousands of scientific articles published on this topic (see Wolfe, 1998). A standard visual search experiment consists of a target, surrounded by several distractors, which are differentiated on the basis of one or two simple visual dimensions (for example, a 'Q' amongst 'O's, a 'T' amongst 'L's or a red horizontal line amongst green horizontal lines and red vertical lines). These items are typically presented on a computer screen that lies completely within the participant's visual field. One of the key findings from this paradigm is that the slope of the function relating search time with the number of to-be-searched items varies with different types of target. When a target can be detected on the basis of a single feature it is found efficiently, and there is little or no cost of increasing the number of distractors surrounding the target. The target is said to "pop-out" and be automatically selected by parallel processing of all the items in the visual field. When targets are defined by multiple, conjoined features they are more difficult to locate and search is thought to proceed with the serial allocation of visual attention (Treisman & Gelade, 1980).

A related concept to the case of a pop-out target is bottom-up attentional selection. This is defined as selection that is determined by properties of a stimulus (e.g., its contrast with the distractors). Bottom-up attention can be distinguished from top-down attention, with selection in the latter case being controlled according to the knowledge of the observer. In a search task, the searcher has a certain amount of top-down knowledge about the target which can guide attention. For example, if the target is known to be a certain colour, attention can be guided towards items of that colour, resulting in a more efficient search. However, in some situations, the most conspicuous item in the display appears to capture attention – bottom-up—regardless of the observer's task (Theeuwes, 2004).

Search in the real world

If we now consider examples of search from our everyday experience, as articles on this subject often do, it becomes clear just how different they are from visual search in the laboratory. Think of the last time you located your keys on your desk or your car in the parking lot. How do these tasks differ from the model tasks used in cognitive science laboratories? First, the target is often not in the visual field at the onset of search. Occluding items or obstacles may have to be moved in order to see or access the target. Second, locating the target normally requires a whole sequence of complex actions in order to bring said object into view so that it may be recognized and used. Eye, head and whole body movements must be made in order to locate the target, and in some cases the searcher must change significantly their own location within the environment. Third, targets and background are often complex and defined in terms of a whole range of features.

One of the ways in which researchers have sought to bring visual search experiments closer to real life is to increase the complexity of the targets and the background in which they are presented. For example, observers may be asked to search for pictures of realistic objects within an array of multiple images (Chen & Zelinsky, 2006; Foulsham & Underwood, 2009; Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004, Exp. 5). Using these arrays allows experimenters to control the number of items and their location, but increasing the complexity of the stimuli comes at a cost: it becomes more difficult to quantify the visual features which distinguish targets from distractors. Other experiments have investigated what has been called "real world search" where observers search for objects within photographs of natural scenes (Foulsham & Underwood, 2007; Henderson, Malcolm, & Schandl, 2009; Neider & Zelinsky, 2006). For example, Neider and Zelinsky (2006) asked people to look for tanks and helicopters in photographs of outdoor environments, and Foulsham and Underwood (2007) showed photographs containing pieces of fruit within interior scenes. Because of the relative complexity of these scenes, observers make eye movements in order to direct their attention, and experimenters can track the course of these eye movements to get a comprehensive record of the regions of the image that are being selected. One of the difficulties in relating these real world search tasks to more simple visual search is that in real scenes it is not clear how one should define the number of items in the display (although measures of visual clutter might be useful in this respect; see Henderson, Chanceaux, & Smith, 2009; Rosenholtz, Li, & Nakano, 2007).

It is also difficult to quantitatively assess the degree to which real objects "pop-out" from their background. The dominant framework for modeling the selection of different items within a scene remains a feature-based approach, exemplified by Itti and Koch's (2000) computational model of visual saliency.

Unfortunately, bottom-up visual saliency defined in this way seems to have little predictive power in a realistic search task (Chen & Zelinsky, 2006; Foulsham & Underwood, 2007, 2009; Henderson, Malcolm, et al., 2009). Instead, it is thought that participants are guided towards targets in real-world scenes by their knowledge of what the target looks like and where it is likely to be located. For example, when looking for pedestrians in street scenes observers tend to fixate regions close to street level, and when looking for paintings they scan the walls (Torralba, Oliva, Castelhano, & Henderson, 2006). Such top-down expectations seem to dominate in real-world scenes (Eckstein et al., 2006).

Real world search tasks have allowed some aspects of realistic visual search—namely the complexity of the target and the presence of real-life expectations—to be studied while maintaining the control afforded by a laboratory situation. Other researchers have studied specialist classes of search conducted in real life—such as that accomplished by baggage security inspectors or radiologists looking for tumors (e.g., Godwin et al, 2010). Moreover, there is a long tradition of applying concepts from attention to specific real world tasks such as air traffic control and driving (see, e.g., Wickens & McCarley, 2010; Crundall & Underwood, 2008).

Despite such research, there remains a mismatch between studies measuring eye movements and visual attention in search and the process of looking for something in the real environment. In particular, relatively few studies have looked at visual attention in search where the observer is free to move his or her head and body, or where targets are not already present in the visual field. One notable exception to this is a recent study by Brennan, Watson, Kingstone and Enns (2011) who asked coders, naïve to the search condition, to rate video clips of people hunting for objects in an actual room. This study found that reaction time (which is the dominant measure of search performance in the lab) could be supplemented by coders' ratings of head and eye movements to measure the efficiency of the search process. Looking at search on a larger scale, and allowing people to move their bodies, has also been useful in comparing visual search to foraging tasks in humans and other animals (e.g., Smith, Gilchrist, & Hood, 2005).

The importance of generalizing to an active search task

A possible criticism of much of the research into search in scenes is that it is based on static picture viewing. Tatler, Hayhoe, Land and Ballard (2011) recently argued that such research does not represent the dynamic, active and task-driven nature of vision in the real world. They review what has been learned from gaze allocation in real world tasks where participants are free to move around (e.g., Hayhoe, Shrivastava, Mruczek, & Pelz, 2003; Land, Mennie, & Rusted, 1999). As in search, these tasks involve active attentional selection because participants must find the correct item for the next component of the task. For example, before making a sandwich, participants looked equally often at relevant and irrelevant objects, but when they started to act they became more focused. Sandwich makers had to pick up a knife, open a jar and so on, and at each point they fixated the relevant information. This is an example of top-down attention in a real world context. Our approach in the present study was to use a mobile eye tracker to monitor attention during a realistic search task, thus providing an opportunity to test the lab-derived principle of bottom-up selection in natural behaviour.

Tatler et al., (2011) discuss a number of assumptions that are implicit in bottom-up models of gaze allocation. It is assumed that simple features are parsed pre-attentively and thus drive fixation selection in some "default" bottom-up mode of looking, and that the spatial priorities of such a system are largely constant over time. The authors argue that these assumptions are problematic given the weak correlation between visual features and fixation, and the temporal coupling of gaze to actions during natural tasks. Many of these assumptions are equally present in models of visual search. In computer-based visual search, bottom-up selection of pop-out stimuli is found frequently, and there is also good evidence that some stimuli such as sudden onsets are powerful attractors of attention (e.g., Theeuwes, 2004). Presumably, it is important for potential hazards and other "surprising" events to draw observers away from the task at hand. However there is relatively little evidence for the selection of distinctive items in natural behaviour. Tatler et al. note that “it is an empirical question whether attentional capture by large signals…constitutes a significant portion of ordinary oculomotor behaviour”, and that answering this question will “help determine the extent to which results from picture viewing might generalize to natural behaviour” (p.11). The present study begins to answer this question.

A growing number of researchers in the field believe that it is important to test the extent to which the principles of cognitive psychology extend beyond the specific, laboratory-based paradigms from which they are derived (Kingstone, Smilek, & Eastwood, 2008). Specifically, laboratory research into cognition, and visual search in particular, is founded on the critical assumption that human attention is subserved by processes that are invariant and regular across situations (the *assumption of invariance*; Kingstone et al., 2008). Note that the assumption of invariance refers to the fundamental idea that a researcher's discovery of how a process operates within a simple, controlled laboratory situation is considered to be preserved and apply equally to complex, natural situations. It is this assumption, after all, that gives researchers the license to generalize and apply their findings and conclusions in controlled lab situations to uncontrolled real world environments. There are many reasons to question the validity of this assumption (see Kingstone et al. 2008). For instance, one classic way to examine the invariance of an effect across situations is through replication in strict laboratory conditions. Wienrich and Janczyk (2011) provide a telling example of the failure of this assumption, in the context of bottom-up attention. They sought to replicate the finding that attention is captured automatically by the most salient item in a display regardless of the task set of an individual (Theeuwes, 2004). This view is contrasted by the position that attention is captured by the most salient item only if it overlaps with the task set. After 9 experiments, Wienrich and Janczyk never found a distractor effect and they concluded that: " This is noteworthy since we tried to replicate the original experiment as closely as possible... differences may be due to unspecified experimental or laboratory settings (different response keys, different computers, and so forth)" (p. 2051). As has already been discussed, the differences between visual search in the laboratory and search tasks in everyday life are numerous and profound, so even if a result is replicated within the tightly controlled confines of the lab it may not be reproducible in a natural real world situation.

The present study

The present study therefore seeks to apply principles from visual search in the laboratory to an active search task. In order to provide a bridge between the studies of gaze in real world action and simple visual search in the lab, we use a search task requiring participants to find and retrieve an envelope from a particular mailbox (the target) in a mailroom. Head-centred gaze was recorded using a mobile eye-tracker. The choice of this search task had several advantages. First, it is an everyday task that many people accomplish on a regular basis, and theories from experimental psychology should be able to speak to the performance of such tasks. Second, because potential targets were spread over a large area in a three-dimensional space, the target and distractors were not all immediately present in the visual field and searchers needed to walk around and move their head and body to complete the task. Unlike the majority of visual search experiments participants were free to move around to do this. One of the key advances with this approach is that we are able to measure eye movements and manual reaction time once the target is visible in the central visual field (which is what visual search studies tend to measure in the lab) *as well* as asking how participants move their head and body around the room to bring the target into view in the first place. Despite the novelty of this approach, a third advantage of the mailroom situation was that, because it required locating a single defined target among visually similar targets it can be more readily compared to lab-based visual search. Targets and distractors were embedded in the scene, in the sense that they were not isolated on a monitor, whilst still being clearly defined for the purposes of analysis.

In addition, we introduced two manipulations in order to test the generalisability of principles from visual search in the lab. First, we varied the bottom-up conspicuity of the target mailbox, with the prediction that a distinctive target should pop-out from the surroundings and thus be found more quickly. Second, in a subsequent experiment, we changed the instructions, giving people explicit, top-down knowledge about the mailbox that they were looking for. The question in each case is whether the lab-motivated manipulation will have an effect on a single trial of complex active search, and, if so, how it will impact head and eye movements.

The results will constrain our understanding of search performance because if bottom-up and top-down effects are absent or manifested differently in the mailbox task then these attentional control processes cannot be assumed to be invariant. On the other hand, showing complex situations where these processes continue to operate will reinforce the aspects of search behavior which we should seek to explain both in and outside the lab.

Experiment 1

Method

Participants

Twenty-nine undergraduates (17 female) from the University of British Columbia took part in exchange for course credit. All participants had self-reported normal vision and none wore glasses. Participants gave their informed consent before beginning the experiment.

Apparatus and calibration

We monitored participants' gaze using the MobileEye system (Applied Science Laboratories; Virginia, MA), which consists of two small cameras mounted on a pair of lightweight glasses. The equipment recorded the position of the right eye (using the pupil image and the corneal reflection), and a second camera recorded the scene in front of the observer. The scene camera was adjusted to have a field of view aligned with the participant's line of sight, and both cameras recorded to a digital videocassette recorder that the participant carried in a small backpack on their back. The MobileEye has an instrumental resolution of better than 1°, with a field of view and tracking range of approximately 60° horizontally and 40° vertically. Video frames were recorded at 60Hz and scene and eye images were interleaved, giving an effective temporal resolution of 30Hz.

Calibrations were performed before and after the search task by recording gaze while participants fixated each of 9 points that were marked on the wall of a testing room with similar lighting conditions to the mailroom. Calibration points spanned the field of view and were positioned approximately 2 metres from the participant, which roughly reflected the distance at which we expected people to fixate the objects of interest. Calibrations were repeated until pupil and corneal reflection could be detected by the system for all 9 points. Data from 2 participants were discarded because their calibrations showed significant deterioration after they had completed the task (e.g. because the MobileEye glasses had slipped) and because gaze data was missing for a majority of the time in the mailroom. In the remaining participants, gaze position was available in at least 80% of all frames during the mailroom search, with invalid samples in the remainder due to blinks or tracking failures.

Procedure

Following successful calibration, participants were given written instructions describing the search task and were led to the start point which was a door exiting the laboratory. Participants were instructed that they had to walk through the building to the faculty mailroom. Once at the room, the instructions stated "you need to find our mailbox, which is labeled KINGSTONE LAB. The envelope you need will be clearly marked. Please bring the envelope back to the lab". This task took place in the Douglas T. Kenny building, which houses the Psychology Department at the

University of British Columbia. The present study investigated the participant's search behaviour from the moment of crossing the threshold into the mailroom to successfully locating the target mailbox. Each participant performed the task once, and no participants were familiar with the location or layout of the mailroom before the study. Participants were not told anything about the order or appearance of the mailboxes.

The task required locating the correct mailbox on entering the mailroom, and retrieving the envelope (which was always the only item in the mailbox). The mailbox was contained in an array of approximately 120 highly similar boxes taking up the back wall of the mailroom, straight in front of the door through which the participants entered (see Figure 1 for an example of the scene). Thus finding the mailbox can be construed as a rather difficult visual search task. Mailboxes were 10 cm wide by 32 cm tall, and the target mailbox was 150 cm above the floor. The correct mailbox was inconspicuously labeled with the name of the laboratory (in letters approximately 1 cm high), and all participants were informed of this name. Laboratory mailboxes, including the target, were not in an alphabetical order, and the same target mailbox (to the right of the centre of the array) was used throughout. There were also multiple irrelevant distractors in the room such as posters, photocopiers and other mailboxes.

We manipulated the conspicuity of the target for half of the participants by adding a brightly-colored, pink paper frame which was affixed to the outside of the mailbox (see Figure 1), and which marked it out relative to the other, homogenously colored mailboxes. While some of the mailboxes contained other mail and other items this was unconstrained by the study and participants were given no other information about what would be in the target box. In the terms of experimental psychology, the "pop-out" mailbox was a singleton which differed by its unique colour.

Figure 1. Frames from the MobileEye scene camera, capturing the environment of a participant entering the mailroom and searching for a particular mailbox. The target mailbox was either indistinct (bottom left) or made conspicuous by adding a colored border (bottom right).

Results

Data analysis

Gaze information from the eye camera was combined with the view from the head-mounted scene camera using software from ASL. This software generated a 30 frames-per-second video in which the point of regard at each point in time was superimposed over the scene with a red cursor. As well as looking at the time each participant took to find the target, the videos were hand coded using customwritten software to test several hypotheses about where people would look during the search. Coders recorded a fixation whenever eye position remained on an object for at least 2 consecutive frames (i.e. longer than approximately 66ms). An example of the video data is available online from the first author's website.

Search behaviour

We defined overall search time as the time between entering the mailroom and touching the envelope in the correct mailbox. One participant (from the homogenous mailbox condition) failed to find the correct mailbox and data from this participant are excluded from further analyses. The remaining participants took 32.1s on average to find the target (*SD*=19.3s).

Although extensive evidence from visual search in the laboratory suggests that colour singletons should pop-out and be found more quickly, the pop-out mailbox was not found any quicker than the homogenously coloured mailbox (in fact it was found slightly less quickly, but there was no significant difference, see Figure 2, left; $t(24)<1$).

Participants made multiple head and eye movements before finding the target. Not all distractor mailboxes were fixated. Participants spent time fixating both the textual label of the mailbox and the items inside, although 39% of the non-targets looked at were empty, suggesting that selection was not only reliant on mailbox content. To look at the process of acquiring the target, and investigate any differences between homogenous and pop-out searches, we recorded the frequency and time of two key events.

First, we coded the occasions when the target entered the scene camera's field of view. Note that this does not map exactly on to the field of view of participants, who have a maximum horizontal field of view of almost 180°, larger than that of the scene camera (which was approximately 60°, see Method). Moreover, because the scene camera view is not determined by eye position it does not provide a precise estimate of the retinal eccentricity of objects. However, despite these limitations, it is an excellent measure for a number of reasons. First, changes in the scene camera view give a measure of head movements. In Brennan et al., (2011), the rate of head movement, rather than exploration with eye movements, was found to be the best predictor of search efficiency in a real context. Second, the actual visual field used by humans is normally assumed in clinical and applied contexts to be much smaller than the physical field of view. For example, legal standards in the UK consider intact vision in the central 120˚ to be sufficient for driving and perimetry often tests only the central 30˚. The "useful field of view" when under conditions of attentional demand is much smaller than the physical field of view (it is often evaluated in the central 60˚), and the size of this region is predictive of performance in real world tasks such as driving and walking (Ball & Owsley, 1993). We therefore thought that it was unlikely that items far outside the view of the scene camera would be influential during this task, and our data support this. Thirdly, in another study with the same apparatus people tended to fixate largely in the centre of the head frame-of-reference, and they sampled the environment using larger head and body movements, followed by smaller eye movements (Foulsham, Walker & Kingstone, 2011). It has also been observed in non-human primates that head direction is a sensitive indicator of visual attention (Shepherd & Platt, 2008). In the present study, we observed that participants often made a head movement (which directed the scene camera) to one part of the scene, and then, with the head relatively still, fixated a sequence of points around the centre of this frame-of-reference. The entry of the target into the view of the scene camera can therefore indicate that it is within central vision and more available for selection by covert attention or fixations than when it is not in the scene camera's field of view.

The second main event we coded was each discrete fixation on the target, prior to the participant reaching for the envelope. A fixation on the target confirmed that its features have been selected and scrutinized by foveal vision. This may be particularly useful given a recent study showing that the best predictor of visual search efficiency on a monitor was the time to respond once the target had been fixated (rather than the time taken to get there; Watson, Brennan, Kingstone, & Enns, 2010). By coding these events, we asked whether, despite search times being equivalent, homogenous and pop-out targets were selected differently by head and eye movements.

The target was normally acquired on the first or second occasion that it was brought into the scene camera field of view (mean number of entries into field of view=1.7). However, the likelihood of participants finding the target the first time that it was within the field of view was greater for pop-out targets than homogenous targets (see Figure 2, right). This was confirmed by a chi-square test of association which demonstrated a significant relationship between target salience and the likelihood of finding the target the first time it was within the field of view, χ^2 (1, N = 26) = 3.8, p<.05. In other words, participants searching for homogenous targets were more likely to "miss" fixating the target when their head was pointing in the right direction, make an additional head movement and return later. The majority of participants made only a single fixation on the target before reaching for the envelope, and this did not differ between conditions (mean frequency of target fixations=1.2, t(24)<1).

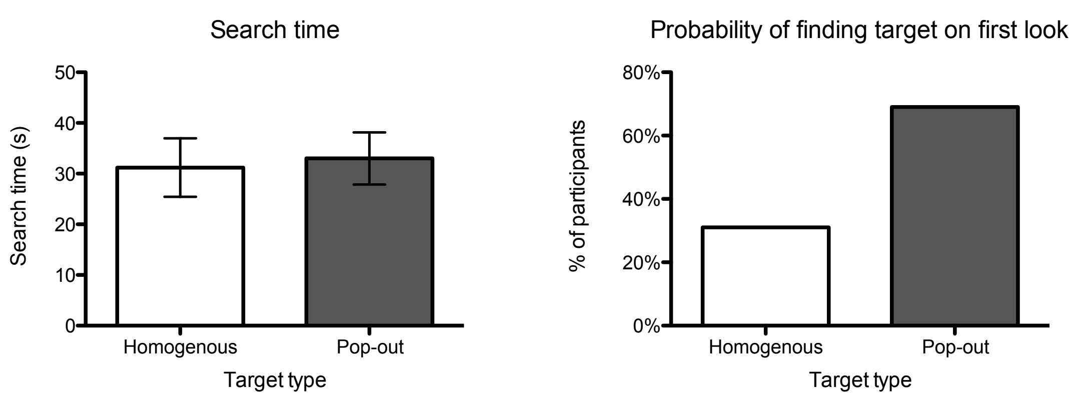

Figure 2. The mean search time (left, with standard error bars), and the probability of a target being found and reached for on the first occasion that it was in the visual field (right), for the two types of target.

The timing data was used to divide the search time period into different epochs depending on how the participant was searching. First, we defined the period between entering the room and bringing the target into the line of sight as "head and body search", as during this period, participants were moving their head and body to orient towards different parts of the room and the array of mailboxes. This epoch was demarcated by the final time that the mailbox was brought into the scene camera's field of view before it was found. Although, as we have noted, the camera's field of view did not map perfectly on to the participant's visual field, based on the behaviour we observed this was a reasonable estimate of the moment when participants stopped moving their head and body and concentrated on a single part of the mailbox array. Second, we defined the time from bringing the correct mailbox into the camera's field of view until first fixating the target as "eye search" as during this time participants often made several eye movements to different boxes while the target remained in view. Finally, we defined "reach time" as the period between participants first fixating the target and them touching the envelope. As participants tended to make only a single fixation on the target before reaching, we interpret reach time as consisting of the time taken for the participant to identify that the fixated mailbox is in fact the correct target, followed by the time to initiate and execute a reach. Splitting the search time in this manner is similar to the way that the measurement of eye movements in computer-based visual search has been used to disentangle different parts of the reaction time (Malcolm & Henderson, 2009; Watson, et al., 2010; Zelinsky & Sheinberg, 1997), but here we sought to describe the stages involved in our unconstrained, active search task. Figure 3 shows the search time broken down in this way.

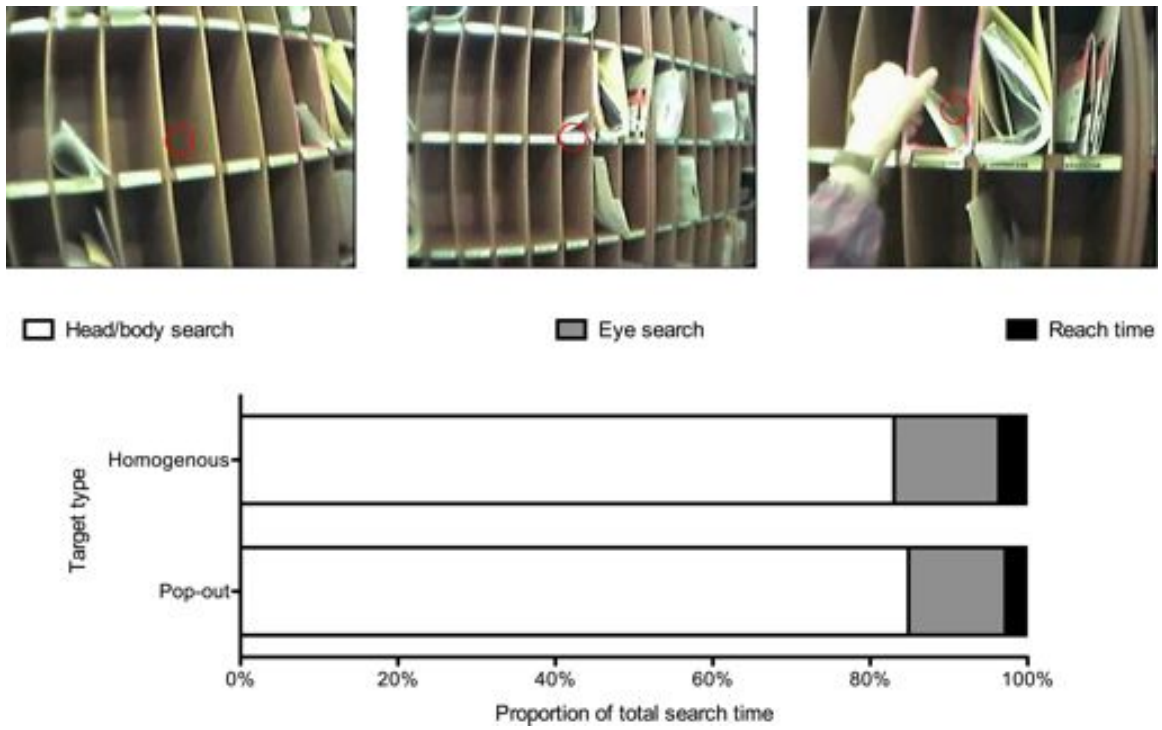

Figure 3. The mailbox search task could be broken down into several stages. The proportion of the total search time for the two conditions is shown in the chart (bottom), with frames from the scene camera illustrating the events dividing the three epochs (top). Head/body search ended when the target mailbox was brought into the line of sight of the scene camera (top left). Eye search ended when a fixation was made on the target (top middle). Reach time included the time until reaching for the envelope (top right).

In both conditions, the subdivision of the search time was very similar. Participants spent the majority of the time moving their head and body around the room and the mailbox array, at which point the target was not yet within their central visual field (as defined by the field of view of the scene camera). Head and body search comprised about 80% of the search time, or an average of 26s. The eye search epoch, at which point the target was within the field of view and exploratory eye movements were being made, was 4s on average, and participants took a subsequent 1s to recognize the target and reach for it. Although participants searching for a pop-out target took slightly less time to fixate the target, and they also reached for it slightly more quickly, there were no significant differences between the two conditions (all *t*s(24)<1.1, all *p*s>.3).

The target and distractor mailboxes were arranged in a grid. In visual search in the laboratory, it has been observed that grid searches sometimes elicit systematic searches, particularly over multiple repetitions (Scinto, Pillalamarri & Karsh, 1984; Gilchrist & Harvey, 2006). Such strategies are of interest in a natural or applied context (e.g., Huestegge & Radach, 2012), and it is also possible that they overrode some of the effects of bottom-up saliency in the present study. On the other hand, we note that the previous lab-based studies that have observed strategic shifts of attention have done so within the central visual field. It was here, when the target was within the 60˚ field of view of the scene camera, that we did find a difference between pop-out and homogenous targets in that the former were less likely to be passed over before being fixated. Nevertheless, we also looked at possible contributions of systematic strategy to search time by coding how participants searched the array of mailboxes. There was certainly evidence for a systematic strategy: 73% of participants started their search on the left side of the room and 46% began by looking at a mailbox in the top left of the array. The incidence of these strategies was not reliably associated with target condition (chi-square tests of association: $\chi^2(1, N=26) = 0.5$, $p=.47$ and $\chi^2(1, N=26) = 2.9$, $p=.09$, for likelihood of starting on the left and gazing first on the top left, respectively). The remaining participants tended to start in the centre and, tellingly, no participant started by looking at the right side of the room. The search times of participants who did and did not start on the top left of the mailbox array were not reliably different (*M*s = 34.8s and 29.8s, respectively; $t(24)<1$). There was also no association between this strategy and finding the target on the first opportunity ($\chi^2(1, N=26) = 0.6$, $p=.43$). Therefore, although we could detect systematic strategies in this task these strategies did not have a large impact on search time.

Experiment 2

Experiment 1 demonstrated the use of a realistic search paradigm where participants were free to move around. There were at least two interesting findings. Unlike traditional lab-based studies where all the potential target locations were equally available at the same time, the number and locations of the mailboxes demanded that participants move their bodies, head and eyes to fixate a subset of the possible target locations. When overall search time was measured, there was no effect of the bottom-up saliency of the target. Bottom-up target conspicuity has also been shown to have a limited effect on search in photographs of real world objects (Chen & Zelinsky, 2006) and scenes (Foulsham & Underwood, 2007).

However, in the present study it is apparent that for much of the search time the target was not within the central field of view and participants were instead moving their head and body around the room (driven by strategy and expectations about where the target might be). The question thus became how likely would participants be to find the target once it came into view. On this score, the data were clear-cut: if the target was distinctly colored it was more than twice as likely to be found on the first opportunity (69% vs. 31%), a reliable effect. That a uniquely colored mailbox could capture attention, even when participants did not have a top-down set for that particular singleton, is what some previous lab-based data would predict (Wolfe, Butcher, Lee, & Hyle, 2003). Despite recent failures to replicate the finding that bottom-up singletons automatically capture attention in search (Wienrich & Janczyk, 2011), the present study reinforces the presence of bottom-up selection processes in real world, active tasks.

The pop-out mailbox was different from the mailboxes surrounding it, a high contrast change which informal testing confirmed could be perceived in peripheral vision. Therefore, we interpret the fact that it did not affect search until it was within central vision as evidence of an attentional limit, rather than a perceptual one. One way to confirm this interpretation is to see whether, when primed to attend to this feature, participants can move toward the mailbox more quickly. In Experiment 2, we changed the instructions to give people a top-down expectation of target appearance. An additional group of participants completed the mailbox task, but were told that the mailbox they were searching for had a bright pink border. In many experiments in simple and real-world computer-based search, top-down set (e.g.. knowing what to look for) has a dominant effect on attention. We would therefore predict that the target should be found more quickly and the experiment asked how the gaze behaviour differs in this case.

Method

Participants

A new group of 19 participants (12 female) from the University of British Columbia took part in exchange for course credit.

Apparatus

For this experiment, a newer model of eyetracker was used. The Tobii Glasses eyetracker records gaze position in freely moving participants using scene and eye cameras built into a pair of glasses. As in Experiment 1, data was recorded at 30 Hz and the scene camera gave a slightly smaller field of view of 56° horizontally x 40° vertically. The system was calibrated and coded in the same way as in Experiment 1, and provided a record of gaze position accurate to the nearest degree, and written as a cursor overlaid on to each participant's scene video.

Procedure

The procedure was the same as that in Experiment 1: participants were given instructions to go to the mailroom and retrieve an envelope from a particular mailbox. However, in this experiment, participants were told that they were looking for a mailbox with a pink border, therefore giving them a top-down cue to the target.

Results

The results were analysed in the same way as in Experiment 1 and focused on the time to find the target and the patterns of head, body and eye search made during the search. Two participants were excluded due to a large amount of missing data during the mailroom task, which was attributed to calibration errors. Mean data from the remaining participants was compared to those from the Homogenous and Pop-out conditions from Experiment 1.

Search behaviour

The participants in this experiment, who had prior knowledge about the appearance of the target mailbox, were considerably faster to find the target than in Experiment 1. The mean search time (from entering the room to touching the envelope) was 8.0 seconds (*SD*= 5.3). This was significantly quicker than the Homogenous condition in Experiment 1 ($t(28) = 4.4$, $p<.001$). More important, participants with prior knowledge were also much quicker than participants from the Pop-out condition in Experiment 1, who were looking for exactly the same visual target but had limited top-down information ($t(28) = 5.3$, $p<.001$). Top-down instructions had a large effect on the search task.

In Experiment 1, the homogenous mailbox was often passed over without being found: it came within the central field of view (as defined by the scene camera) without being fixated or found. This happened less often with a conspicuous target. In the present experiment, the target was brought into the scene camera's field of view on a similar number of occasions (mean number of entries = 1.65). The target was found on the first pass in 53% of searches. This is slightly less often than when the same pop-out target was used in Experiment 1, but there was no significant difference ($\chi^2=0.8$, $df=1$, $p=.4$). In most cases, only a single fixation was made on the target before it was reached for.

We also divided up the search time in the same way as in Experiment 1. This analysis will provide information about whether the overall reduction in search time was associated with a change in the time spent moving around the room and making head movements ("head and body search"); the time spent making eye movements when the target was in the visual field ("eye search"); or the time spent reaching the target after it had been identified ("reach time"). The average proportion of time spent in each of these epochs is shown in Figure 4.

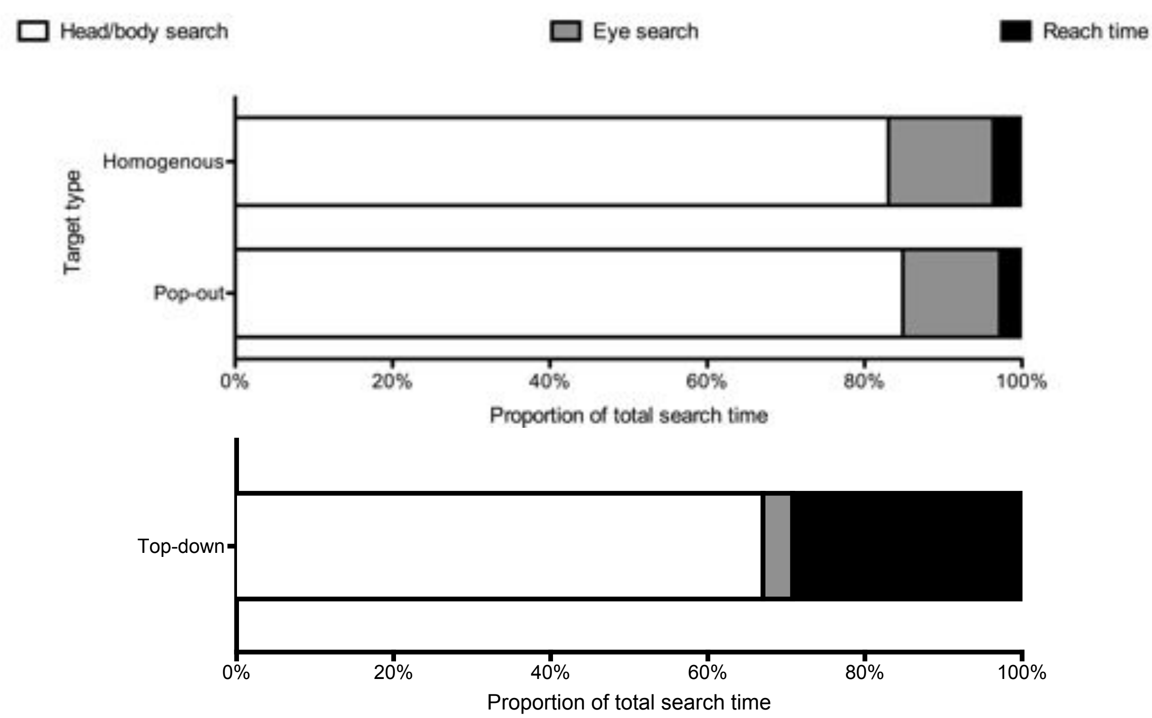

Figure 4. A breakdown of the active search process in Experiment 1 (top, duplicating the data from Figure 3) and in Experiment 2 when participants had a top-down set matching the pop-out target mailbox (bottom).

Given that the search task was completed much quicker in this experiment, we would expect each part of the search to be significantly quicker than that in Experiment 1. In fact, although head and body search (*M* = 5.4s) and eye search (*M* = 302 ms) were greatly reduced in this experiment, reach time (*M* = 2.3s) was actually longer when participants had top-down information about the target's distinctive border. Head and body search and eye search were significantly quicker when compared to the pop-out condition in Experiment 1 (both $ts(28) > 4.8$, $ps<.001$). Reach time was significantly slower ($t(28) = 5.0$, $p<.001$). When considered as a proportion of the overall search time (see Figure 4), it is clear that, in Experiment 2, the relative amount of time spent moving the body, head and eyes around the room was dramatically reduced, and that the time between fixating and touching the target contributed more to the duration of search. Examination of participant behaviour in this experiment showed that the increased reach time resulted from participants first fixating the mailbox from much further away, and with less exploration of the room. For example one participant walked into the room, made a single head movement bringing a group of multiple mailboxes, including the target, into the scene camera's field of view, and fixated the target border almost immediately (i.e. with very little "eye search" time). The majority of the search time was therefore taken up with the time spent walking to and reaching for the target.

General discussion

The present study aimed to describe search in a real world context, where participants were free to move around (as in studies of gaze in natural behaviour: Hayhoe et al., 2003; Land et al., 1999) but where there was a defined target whose distinctiveness amongst an array of similar distractors could be manipulated (as in lab studies of visual search). More generally, the results begin to address concerns expressed by Neisser (1976), Broadbent (1991), and more recently Kingstone et al., (Kingstone, et al., 2008; Kingstone, Smilek, Ristic, Friesen, & Eastwood, 2003), who have argued that the findings of cognitive psychology may not extend beyond the specific paradigms in which they are derived. The present study took this challenge head on by investigating in a natural, complex, real-world situation arguably the most fundamental paradigm-based principle in human attention research: that visual search performance is affected significantly by top-down and bottom-up processes. There is a wealth of information that this principle holds when studies are conducted in a traditional, controlled lab environment (Foulsham & Underwood, 2007; Treisman & Gelade, 1980; van Zoest & Donk, 2004; Wolfe, 1998; Wolfe, et al., 2003). On the other hand, even small changes in lab conditions can affect, for example, the robustness of bottom-up distraction (Wienrich & Janczyk, 2011). Moreover, as noted by Tatler et al., (2011), it is not known how often gaze in natural behaviour is captured by salient and surprising signals in the environment. It is therefore an open question whether the principle of bottom-up selection will apply when participants are free to move about in search of a target. In the present study participants moved around a mailroom looking for an envelope placed in a particular mailbox. This study advances both methodology, by illustrating how control can be introduced into a realistic search task, and theory, by examining the influence of bottom-up and top-down factors on the different components of active search and thus testing the assumption that search processes are invariant with context (see Kingstone et al., 2008).

In Experiment 1, bottom-up search was manipulated by making the targeted mailbox in the mailroom either visually distinct by surrounding it with brightly colored paper or visually equivalent to the other mailboxes by removing this border. Mailbox saliency was manipulated between participants. Unlike traditional lab-based studies, there were a large number of mailboxes spread over many locations in three-dimensional space. As predicted by research in active tasks (Brennan et al., 2011; Hayhoe et al., 2003), participants directed their body and head to focus on a subset of the possible target locations, and they then fixated items by making eye movements within the central visual field. Searchers used whole-body, head and eye movements to acquire the target, rather than remaining stationary and searching the visual field with covert attention and/or eye movements alone. Clearly, there is a lot more to this and other natural search tasks than shifting attention between items already in the visual field and then comparing them to a target representation. An important question, therefore, is whether a bottom-up singleton (the uniquely coloured, pop-out target) would make a detectable difference to search efficiency. An initial assessment of search time showed that mailbox saliency had no effect.

One interpretation of this effect is that, in the absence of a top-down set for bright pink mailboxes, target saliency does not have any effect on active search in the real world. Object saliency has been argued to have no effect in other investigations of real world search (in images of scenes; Foulsham & Underwood, 2007) and active behaviour (Rothkopf, Ballard, & Hayhoe, 2007). The robustness of bottom-up attentional capture in computerized paradigms has also recently been called into question (Wienrich & Janczyk, 2011). Although we did not give participants specific information about the layout of the room, we cannot rule out the possibility that preconceptions about the mailroom contributed to participants checking probable locations while ignoring the singleton. For example, they may have assumed a systematic or alphabetic order of the mailboxes, and this may partly explain the strategy of many observers of starting at the top left. However, given the name of the target mailbox, if participants were in fact guided in this way we would expect them to start near the middle of the array which only happened about half of the time.

Our measurements included the time spent walking and making head and body movements. This meant that we were able to carry out further analysis that suggests a different interpretation of the lack of an effect on overall search time. The majority of the search time consisted of head and body movements. For much of the time in the mailroom, the target was not within the visual field, and it was frequently not within the central visual field (as defined by the field of view of the scene camera) and therefore was unlikely to capture attention. As a consequence of this the saliency of the target mailbox had only a limited opportunity to affect overall search behaviour at this scale. There were, however, trends for it to be fixated and reached to more quickly, and salient targets may have been pre-attentively selected by covert attention, making it more likely to be fixated and identified when in the visual field. Furthermore, there was a reliable effect of target salience on the likelihood of the target being found when it was first brought into the scene camera's field of view (and therefore was within 30˚ of the centre of head direction). By this account, stimulus-driven bottom-up processes affected attention to the target once it was brought into the central field of view, but not in peripheral vision. This is consistent with data from the lab (Wolfe, et al., 2003). If the target mailbox was visually unique it captured attention and meant that it was less likely the searcher would move on by making additional head movements. There was no difference in the number of fixations made on the target, and the mailbox was almost always found on the first fixation, so this difference between conditions must have emerged due to the pop-out mailbox being more readily identified in extra-foveal vision. There was also no difference in the time taken to direct the head towards the target, bringing the mailbox into the scene camera view (what we have called "head / body search"), which confirms that the singleton was not prioritized, when it lay beyond the scene camera's field of view (and therefore more than 30° from the centre of the head frame of reference).

Our approach enabled us to detect an effect from the lab (the guidance of attention to a bottom-up salient target) but also to describe how it was manifested in active search. Of course, because the experiment took place in a naturalistic environment, the stimuli varied in ways beyond our control. For example, the contents of the distractor mailboxes varied from trial to trial and may have also been brightly coloured. None of these extraneous bottom-up differences were predictive of target location but they may still have reduced the relative salience of the target. However, the distinctive target border did affect looking behaviour. This reinforces the robustness of our finding that it had a significant effect despite the natural variation and competition from other stimuli. Nevertheless, one way to continue bridging the gap between computerized tasks and real search would be to selectively control other bottom-up factors such as the contents of the boxes and the lighting in the room. Additional research could also investigate a range of pop-out targets distinguished by different visual features or which are more or less conspicuous.

In Experiment 2, a new set of participants repeated the mailbox search task with the knowledge that their target had a pink border. This introduced an additional top-down signal, which coincided with the bottom-up salience of the target mailbox. When search in this condition was compared to the pop-out condition from Experiment 1 (where participants searched for the same, brightly coloured mailbox but without the top-down knowledge), search was much quicker. Participants who knew what they were looking for required less than a third of the time taken by participants in Experiment 1. This was a large effect, demonstrating that, despite the variability expected due to different moving speeds and strategies, this method can be used to detect differences between search conditions. Search instructions affected the stimuli that were selected and attended in a top-down manner, and this dovetails with a wealth of lab-based studies showing that a minor variation in stimulus instruction will alter the participants' attentional set and the way they select and attend to information within the search environment (eg., Desimone & Duncan, 1995). Using our controlled but realistic paradigm, future research could explore this further by manipulating the salience of the distractor mailboxes. Of course, the top-down, task-based allocation of gaze is a theme that is common to much of the existing literature on eye movements during real actions. For example, Turano, Geruschat and Baker (2003) recorded the gaze of 4 participants walking toward a particular door in a corridor. They found that the best model for predicting gaze locations was one that had top-down knowledge about the target door (that it was on the left side of the corridor and had straight, vertical edges), and that such a model outperformed bottom-up visual saliency. Other detailed investigations of gaze during action converge on the fact that gaze is highly specific to the task at hand (Hayhoe, et al., 2003; Land, et al., 1999; Rothkopf, et al., 2007).

Our study has the advantage that it draws a clear link between visual search methodology in the lab and search in real life. Howard, Pharaon, Koerner, Smith and Gilchrist (2011) provide another recent example of using mobile eye tracking to extend findings from a computer-based task to a more realistic setting. In their study, Howard et al. asked participants to perform a series of searches for a target object amongst a set of other objects placed on a tabletop. The results replicated a finding from a standard computer based search task—that search is faster when a display is repeated—and thus provided further evidence for the representation of distractors between searches. The authors note, as we have done, the theoretical and empirical importance of demonstrating that results transfer from computerized displays to larger scales and real objects. Mack and Eckstein (2011) also used a tabletop collection of objects and a mobile eyetracker to monitor fixations during a search task. The results showed that participants used the co-occurrence of contextually related objects—such as headphones appearing next to an iPod—to speed search and guide their eye movements. Like that study, the present experiment emphasizes that it is important to examine search when participants are free to move their head in more naturalistic conditions, and shows the influence of top-down cues in such a situation. However, our study moves beyond a tabletop and towards examining attention during the exploration of a whole room, while still making contact with traditional visual search.

As well as being quicker overall, the behaviour of participants in Experiment 2 can be investigated to see how active search strategy was affected by the top-down signal. The data showed that participants did not need to spend as much time moving around the room and making head and eye movements to different parts of the mailbox array. Indeed, they spent a smaller proportion of their search time gazing at other parts of the room in an attempt to bring the target into the visual field, and they normally fixated the conspicuous target as soon as it was within the centre of the scene camera's field of view. This is in contrast to Experiment 1, where there was limited evidence that search was guided more quickly to the pop-out mailbox than to one that was inconspicuous. If we take the entry of the target into the scene camera's field of view as a measure of a head movement aligning central vision with the vicinity of the target, doing so earlier in a particular condition would be strong evidence of guidance to the target from further away. Such guidance could be due to top-down information about target location, for example knowing that the target was on the left of the room, and this could be tested in future research. Alternatively, and in the present experiments, it must reflect peripheral vision: seeing the target at an eccentric location in the visual field and moving the head and eyes accordingly. Importantly, there was no difference in head / body search time between a homogenous and pop-out mailbox in Experiment 1. The bottom-up salience of the target did not result in quicker detection in peripheral vision. In Experiment 2, meanwhile, when participants were searching for a distinctive mailbox they used this top-down knowledge to detect the target and focus quickly on its vicinity. That participants were faster to move their head towards the mailbox in Experiment 2 confirms that the pop-out mailbox was perceivable and that the failure to find it more quickly in Experiment 1 was a result of attention. Participants in Experiment 2 could detect the mailbox "out of the corner of their eye" as soon as they came into the room and begin reaching for it very quickly. This also explains the somewhat counterintuitive finding that "reach time" was longer in the top-down condition. Because participants in that condition detected the target when further away, and because we defined reach time as the time from fixating the target to touching it, the reach time there included walking across the room, which took several seconds, as well as the act of reaching with the hand.

Collectively these data provide a demonstration that top-down and bottom-up processes can be measured in a natural real-world visual search task. This is qualified by the fact that the bottom-up effects in Experiment 1 were relatively minor, whilst top-down instructions had a much greater effect on search. At the scale of our complex search task, the difference in performance for different targets was eclipsed by variability in the behaviour for the majority of the search, i.e., the head and body movements that were not affected by bottom-up target salience until the target was within the central visual field. Very few studies have examined the detection of complex targets in the far periphery, or strategies for acquiring a target that is not yet visible, and further research is necessary to determine the environmental and individual factors that promote efficiency at this sub-task. Given recent research showing that attention and eye movements are distributed differently when participants are free to move their heads ('t Hart, et al., 2009; Foulsham, Walker, & Kingstone, 2011) further investigations into active search, both inside and outside the lab, is a promising and timely line of future research.

The present study demonstrates that visual search in particular, and experimental psychology in general, can generate findings and principles that generalize beyond the situations within which they were observed and created (in this case to a realistic active search task). The effect of mailbox saliency on gaze provides an important demonstration that bottom-up signals can impact a natural task, although further investigations would be necessary to discover how often this happens in other situations (c.f., Tatler et al., 2011). For experimental psychologists who are doing traditional lab-based investigations, in particular those studying visual search and its implications for real-world environments, these data provide evidence about how their results and conclusions may "scale up" to human behaviour in real world environments, as well as identifying complex aspects of search that are ripe for future study.

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