Perception, 2008, volume 37, pages 1729 – 1744

doi:10.1068/p5944

Training eye movements: Can training people where to look hinder the processing of fixated objects?

Richard Dewhurst, David Crundall
School of Psychology, University of Nottingham, University Park, Nottingham NG7 2RD, UK;
e-mail: lwxrcd@psychology.nottingham.ac.uk; dec@psychology.nottingham.ac.uk
Received 5 November 2007, in revised form 21 April 2008; published online 27 October 2008

Abstract. An experiment designed to test the effects of different forms of training in a visual-search-like task is reported. Observers were presented with a series of displays containing a central letter and a ring of peripheral characters, one of which was a digit. Odd digits (catch trials) required a space-bar response; even digits required a different response contingent on the identity of the central letter. Two forms of training provided information either about the location of the peripheral digit, or about a quick way to classify the central letter. The aim was to relate training to Findlay and Walker's (1999, *Behavioral and Brain Sciences* **22** 661 – 721) model of saccadic eye-movement control by affecting the hypothesised Move and Fixate centres respectively. The results showed that training benefited search, but training of the Move centre alone generated significantly longer re-inspections of the central region (in a feedback condition). This highlights that the emphasis often placed upon broadening the range of visual search when training eye movements may be misplaced. More specifically, special attention should be given, not only to advising people how to move their eyes, but also to improving the ability to effectively process important visual stimuli when fixating.

1 Introduction

What are the consequences of training eye movements? Although there are several models of visual attention (eg Itti and Koch 2000; Logan 1996) and oculomotor control (eg Findlay and Walker 1999), these models underspecify the influences of top – down factors, such as training or experience in a specific context. The research described here incorporates eye-movement training into Findlay and Walker's (1999) dual-process model of saccadic planning to suggest that domain-specific experts should be more aware of established models of eye-movement control when developing visual training protocols for use in applied settings.

Findlay and Walker's framework specifies a system where two metrics are programmed for every saccade: 'when' the saccade should occur, and 'where' it should be directed. The model is hierarchical, and although it describes the 'where' and 'when' pathways primarily in functional terms, its lower levels in particular are considerably influenced by work on oculomotor physiology. Accordingly, in processing models of eye movements (Morrison 1984; Reichle et al 1998) 'when' is determined by the processing of the fixated stimulus, and Findlay and Walker link this to activation in the rostral pole region of the superior colliculus, which carries a neural representation of the fovea (Munoz and Wurtz 1993). When processing of the current object has reached a certain threshold, programming of the next saccade occurs. The location of the next saccade is determined by the greatest salience peak represented on a topographic map (cf Munoz and Wurtz 1995a, 1995b), though the intrinsic salience of any object (contours, contrast, etc) may be influenced by top – down factors, such as inhibition of areas of the salience map (Godijn and Theeuwes 2002).

The need to fixate and the urge to make a saccade (represented as 'when' activation in the 'Fixate' centre, and 'where' activation in the 'Move' centre, respectively, within Findlay and Walker's model) are in competition, and are bound together by reciprocal inhibitory links. This has important ramifications for attempts to train eye movements, as any attempt to focus upon one aspect of eye movements may degrade behaviour that is dependent upon the other.

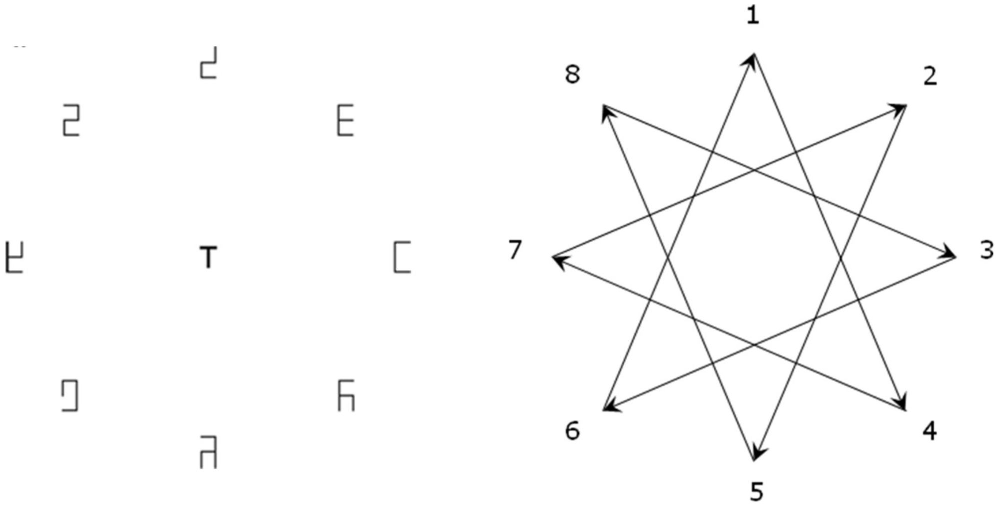
A good example of negative consequences which may be related to this competitive interaction is available in the applied literature on driving. Drivers often fail to see motorbikes at junctions, even though they often report looking towards their location (Clark et al 2004). This phenomenon has been coined the 'look but fail to see' accident causation factor (Brown 2002), and is supported by considerable research (see also Herslund and Jorgensen 2003; Martens and Fox 2007). Here, increased activity in the Move centre associated with vigilantly scanning the visual scene may decrease activity in the Fixate centre when fixated objects are being processed, in this case motorbikes, and as a result they may not be processed adequately despite being fixated. Following this logic, it is unlikely that certain visual-search strategies recommended to drivers, such as repeating a left – right scanpath at junctions (UK Department for Transport 2007) or maintaining active and board visual search (Mills 2005), will be successful in their objectives because they focus upon maximising eye *movements*, which again may decrease activity in the Fixate centre owing to Move-centre competition.

The competitive interaction between the Move and Fixate centres provides a viable explanation why some previous attempts to train eye movements may not have had the desired outcomes. Donovan et al (2005) gave feedback to novice radiographers when they were performing a fracture-detection task. Following this feedback (which showed them where they initially looked on the X-ray and for how long) their eye movements more closely resembled those of expert radiographers. Interestingly, however, the use of an expert scanpath alone was not sufficient to give rise to an improvement in the fracture-detection task. This suggests that advice which changes eye movements alone does not necessarily lead to improvements in performance, possibly because of the type of conflict between the Move and Fixate centres described.

The present research employs a novel experimental paradigm to assess the consequences of directing training specifically at the Move centre of Findlay and Walker's model. A visual-search task was used in which a central letter was presented within a circular array of potential targets (see figure 1a). Participants were required to start each trial by processing the central letter, before searching the peripheral array for a digit amongst non-digits. This design was specifically chosen to require the initial inspection of the central letter (involving the Fixate centre) followed by a series of eye movements (involving the Move centre).

When an even-number peripheral target was located, the required response depended on the central letter: if the central letter was A, T, M, or V, the correct response was to press the '1' key on the computer's number-pad; alternatively, if the central letter was L, F, K, or N, the correct response was to press the '3' key on the computer's number-pad. In contrast, the correct response to odd digits was unrelated to the central letter, a space-bar press being required irrespective of the central letter displayed (these trial types served as catch trials to ensure participants searched the peripheral array and located the peripheral target). Eye movements were recorded while participants completed this task.

The paradigm used provides the opportunity to pre-inform participants about the sequence of locations the target will appear in from one trial to the next; this forms the basis of training directed at the Move centre (see figure 1b), which will be referred to as 'Move Training'. The intention was to create a task where the demands placed on the Fixate centre by the initial letter-discrimination judgment competed with Move centre activation when participants were instructed in 'Move Training'. It is for this reason that correct answers were contingent upon both the central letter and the peripheral number; we sought a task where two items in the display competed for



(a) (b)

Figure 1. (a) An example of one stimulus as shown in a single trial display. The target (the only stimulus in the peripheral array that is a number, in this case the number 2) is located 45° anticlockwise from the 12 o'clock position. (b) The training directed at the Move centre. The numbers indicate place-holder positions for the peripheral stimuli. From trial to trial the peripheral target number appeared in the following sequence: in trial one it was presented in position 1, followed by position 4 in trial two, then positions 7, 2, 5, 8, 3, 6 from one trial to the next (this is indicated by the arrows in the figure). This sequence is repeated throughout all experimental blocks.

attention within a single trial. If, for instance, there was no central letter and participants only responded to the peripheral number (with separate responses for odd and even numbers for example), then the 'Move Training' sequence would induce far less competition between the Move and Fixate centres because the upcoming target location it predicted would be in the next trial. Indeed, this would be the case in any task where Move – Fixate competition was sought inter-, rather than intra-, trial. If the basic task is to be comparable for an untrained group, and 'Move Training' is to be beneficial in improving search performance yet detrimental in reducing information processing at fixation, a task such as the one used here is necessary.

It is predicted that the hypothesised competition induced by 'Move Training' in our task will encourage disengagement from the central letter before it is fully processed. The most obvious way this effect could be revealed therefore is by reduced central gaze durations at the start of a trial, accompanied by less overall fixations and faster search times to locate the peripheral target. However, it is also conceivable on the basis of considerable previous research (eg Engel 1971; Eriksen and Hoffman 1972; Koivisto et al 2004; Motter and Holsapple 2007; Posner et al 1980) that the absolute time spent on the centre upon trial commencement will not change, and the competitive interaction will be expressed as a premature shift of covert attention. Either way, insufficient initial processing of the central letter could lead to the detrimental performance of Move-trained participants in a number of ways: a decrease in accuracy, or participants could need to re-inspect the central letter more regularly after they have identified the peripheral target in order to respond correctly. These possible outcomes would advance our understanding of the eye-movement statistics associated with looking but failing to see.

Given the hypothesis that 'Move Training' may be detrimental to performance because of its effects on the Fixate centre, we also ask whether providing training directed at the Fixate centre, in concert with 'Move Training', can counteract any negative consequences that arise from 'Move Training' alone. Training was directed at the Fixate centre by informing participants that the first set of letters (A, T, M, and V) are all symmetrical around the vertical meridian, whereas the second set (L, F, K, N) are not. Therefore, when initially processing the central letter at the beginning of a trial, the discrimination judgment is reduced in difficulty. This manipulation is introduced on the basis of previous research, cited by Findlay and Walker (1999) as evidence for top – down mediation of the Fixate centre, which shows that, when a stimulus is unchanged but its informational load is decreased, fixation durations decrease also (eg Gould 1973). It is predicted that when directed in *both* 'Move Training' *and* training aimed towards the Fixate centre (this combination of training strategies will hereafter be referred to as 'Both Training') that participants will no longer disengage from the central letter before it is fully processed, and as a result they will not need to re-inspect it as regularly in order to maintain accuracy. 'Both Training' was chosen in preference to 'Fixate Training' in isolation because we wished to demonstrate that any deficits on the task associated with 'Move Training' alone could be ameliorated. In so doing we hope to show that the predicted visual-search benefits of 'Move Training' (in terms of faster search times and fewer fixations per trial) are attainable without any look-but-fail-to-see-like errors. As such, a Fixate-trained-only group would provide little evidence of how visual-training protocols could be improved, because, without explicit direction where to move the eyes, comparable benefits in visual search would not be expected.

Three groups of participants were tested in two blocks of trials. The first block served as a baseline to establish initial performance on the task. For the second block, one group of participants was told the 'Move Training' strategy, another group was told 'Both Training' strategies, and a third and final group was used as a control comparison, being given 'No Training' throughout.

Although it is not central to the main hypothesis, it is conceivable that participants may guess some of the experimental contingencies when they are not advised of the training strategies. Therefore participants were asked upon debrief whether they noticed any of the rules which governed stimulus presentation. This, coupled with a brief examination of typical scanning patterns within a trial, will address questions regarding explicit or implicit learning of the experiment's contingencies. Moreover, a simple examination of the typical scanpaths adopted will also highlight regularities in visual-search behaviour. For example, one may predict, on the basis of previous observations of scanpath uniformity (Foulsham and Underwood 2008), that participants will search the peripheral array in a clockwise or counterclockwise manner (see Findlay and Brown 2006) prior to awareness of the predictable sequence in which the number target occurs.

One final manipulation was introduced into the design. As the study aims to raise awareness amongst researchers in applied domains about the need to refer to established models of eye-movement control when devising eye-movement training regimes, it was thought prudent to assess the effect of feedback upon task performance. The ability to interact with the environment and evaluate the consequences of actions is particularly important in applied settings such as driving, sport, human – computer interfaces, etc, and the source of error monitoring can be internal or external. Therefore, the availability of feedback was varied in the current study, with the second block being equally divided into two counterbalanced sections, one in which visual feedback was always available, and one in which no feedback was provided. Although no specific predictions were made about the effects of feedback, it was anticipated that the performance of untrained participants would suffer most from its withdrawal, simply because this group had no strategy to rely on.

2 Method

2.1 *Participants*

Thirty-eight paid participants (with a mean age of 23 years; twenty-six female) were recruited from the student population of the University of Nottingham. All participants reported normal or corrected-to-normal vision.

2.2 *Stimuli and apparatus*

There were 512 individual stimuli in total; the central letter could be one of 8 possibilities: A, T, M, V, L, F, K, or N; the peripheral number target could appear in one of 8 locations around the centre, and was one of 8 numbers in 'calculator-style' font: 0, 2, 3, 4, 5, 6, 7, and 9 (1 and 8 were not used because they contained too few, and too many component lines, respectively, which could unfairly assist in their detection). Zero was classified as an even number and participants were made aware of this. All of the factors differentiating the stimuli mentioned above were represented with equal probability.

24 non-digit distractors were created by removing one or more component lines from the number 8. Each distractor had approximately the same visual footprint, and different distractors occupied the remaining 7 peripheral locations of the stimulus that did not contain the target. Which distractor occurred in which position was determined at random.

All letters and digits subtended 0.8 deg visual angle horizontally. The peripheral shapes subtended 1.6 deg vertically, while the central letters subtended 1.2 deg vertically. The centre of the central letter was coincident with the centre of the display. The peripheral shapes were located on the perimeter of an imaginary circle, with a radius of 10 deg from the centre, at 45° increments.

A PC operating with a Pentium 3 processor was used to run the experiment via E-prime software. Stimuli were presented on a 19 inch Samsung SyncMaster LCD screen, running at 1024×768 pixel resolution. A desk-mounted SMI Red-Eye III eye tracker was used to record eye movements of the right eye at 50 Hz. Fixations were defined as periods of ocular stability in-between saccades with a minimum duration of 80 ms.

2.3 *Design*

The experiment was divided into two blocks of 128 trials. Baseline performance was assessed in block 1, with no eye-movement training being given. In-between blocks 1 and 2 training was provided for the Move Trained (MT) and Both Trained (BT) groups; the No Training group (NT) acted as a control.

The MT group ($N = 14$) was informed that the target would appear in the predictable sequence shown in figure 1b from one trial to the next. The target was presented in this order with 100% probability throughout both blocks of the experiment for each group of participants. The BT group ($N = 10$) was given an additional strategy to that of the MT group; the participants were made aware that the letters A, T, M, and V (to which the same response is required) are all vertically symmetrical; whereas the letters L, F, K, and N (which also share the same required response) are vertically asymmetrical. The NT group ($N = 14$) was given neither of these strategies.

Feedback was also manipulated for several reasons. First, on the basis of previous pilot work in our laboratory, there was reason to believe that the predicted detriments associated with MT would be most apparent when feedback was provided. Second, because the ability to monitor errors when performing motor tasks is controversial (Hajcak et al 2005; van Veen et al 2004), we thought it prudent to include this measure. The final reason this measure was incorporated into the design was because in applied settings, such as driving, the ability to interact with the environment is vital, and the source of error monitoring can be internal or external.

Feedback was a within-groups factor, with half of block 2 containing feedback (FB) and half not (NFB). The order of this manipulation was counterbalanced across subjects. Throughout block 1 feedback was always given, by way of a red (incorrect) or blue (correct) transient screen after each trial ('time-outs' were considered incorrect). For NFB trials the blue or red mask was replaced by a grey mask in all instances, such that feedback was no longer available.

With the exception of the sequence of peripheral target location being pre-determined, stimuli were selected quasi-randomly. Catch trials (where the peripheral target was an odd number) occurred with 33.3% probability, while trials with an even-number target occurred with 66.6% probability. As the number of trials per block is smaller than the number of stimuli, not all stimuli occurred within a block of trials.

Several dependent variables contributed to the measures taken from the design. Behavioural data in terms of manual reaction times and accuracy were recorded. Several measures of eye movements were also taken. The stimulus array was divided into regions of interest for eye-tracking analysis. A circle, with a radius of 2.9 deg from the centre of the display, was created within which any fixation made was classified as a fixation with the purpose of central-letter processing. Initial central gaze duration, the cumulation of fixation durations from the first fixation on the central letter to the last fixation before this region is left, was calculated. After this initial period of inspection, any fixation made within this central region was classified as a re-fixation. The mean re-inspection duration (ie the average of re-fixation durations for all trials in an entire block, including those in which no re-fixation occurred) was calculated as well as the average number of re-fixations per trial.

Finally, overall visual-search performance was assessed, first by analysing the average number of fixations per trial, and second by analysing the time taken to fixate the peripheral target from the start of the trial. The latter of these measures was calculated by creating regions of interest around the peripheral array items. If a fixation was made outside the area of the imaginary circle designated for the central letter, but within the area of another eccentric circle with a radius 5.8 deg from the centre of the display, it was classified as being unrelated to the processing of any of the displayed items in the stimulus array. Beyond the second eccentric circle, fixations were divided into those on the peripheral number target and those on the distractors. This was done by splitting the stimulus array into regions 22.5° (of a total 360° for the entire stimulus array) either side of centre of the peripheral shapes. If a fixation landed within the target's region it was flagged, therefore allowing the time taken to fixate the target to be calculated. To complement these parametric measures of visual-search performance, representative scanpaths of visual-search behaviour within a trial will be shown for example participants.

For purposes of analysis the data collected were treated in terms of changes in block 2 relative to baseline (although overall means will be given also). For each participant, by subtracting the mean value of a dependent variable at baseline from its mean value in both the FB and NFB portions of block 2, it is possible to quantify relative changes in performance. This controls for idiosyncrasies in ability between participants as the difference score obtained reflects individual change on a given measure as a function of training or, in the case of the NT group, exposure alone.

2.4 *Procedure*

On arrival, informed consent was obtained from the participants. Detailed instruction was available on the computer screen explaining the task, and the experimenter was present throughout to ensure participants understood what they had to do. After the participants agreed to take part and confirmed that they understood the task, the experimenter calibrated the eye tracker (a chin-rest was used to maintain a stable and fixed viewing position of 70 cm from the screen throughout the experiment). Following calibration, participants were initially given a practice block of 30 trials, which were identical to the experimental blocks described below. Once participants had completed the initial practice block, and the experimenter was satisfied that they understood the task, they could proceed.

A fixation cross was presented only at the start of a trial block. A stimulus was then selected according to the stipulations outlined in the design section above. The stimulus remained on the screen until a response was made for a maximum duration of 10 s, following which a feedback mask was presented for 200 ms. Stimulus presentation followed by feedback continuously cycled until the end of a block.

Participants were required to begin each trial fixating the central letter before searching the peripheral array for the target number. When A, T, M, or V were presented in the centre, and the peripheral target was an even number, the correct response was to press the '1' key on the keyboard number-pad; when L, F, K, or N were presented, and peripheral target was an even number, the '3' key on the number-pad was the correct response. When the peripheral target was an odd number the trial was a catch trial, and the correct response was to press the space-bar irrespective of which letter was displayed. Participants were asked to respond as quickly and accurately as possible throughout.

Participants completed the baseline block first, after completion of which the MT and BT groups received their respective training via on-screen instructions. The experimenter also provided explanation if required. Participants were then given a further 30 trials of practice to become familiar with using the training suggested to them. The NT group was given an additional 30 trials practice also, to ensure equal exposure to the task. Following this practice, the experimenter re-calibrated the eye tracker as before.

The second block proceeded next. As feedback was counterbalanced, the order of feedback availability in block 2 varied between participants; they were always informed, however, whether the trials they were about to complete contained feedback or not by on-screen instructions.

On completion of the experiment, participants were debriefed as to the aim of the experiment and its hypotheses. A short questionnaire was also completed in which generic demographic information was collected, along with information about whether the experiment's contingencies were guessed.

3 Results

3.1 *Reaction times (RTs)*

Practice trials, catch trials, and anticipatory responses (RT < 200 ms) were removed before analysis for all analyses described. The average RT to correct trials across groups and conditions was 2859 ms (SD $= 605.6$ ms). Although the behavioural data collected were analysed in terms of difference scores, summary statistics showing the mean in each condition are given in table 1.

The relative effect of training (or practice for the NT group) was calculated by subtracting the participants' mean baseline (block 1) RTs from their mean RTs in both parts of block 2 (FB and NFB). A negative value therefore reflects a decrease, whereas a positive value reflects an increase. These RTs were analysed by a 3×2 mixed factorial ANOVA, with three levels of training and two levels of feedback (this analysis was repeated for all dependent measures taken).

A significant main effect of training was observed ($F_{2,35} = 4.5$, MSE $= 341062$, $p = 0.018$), reflecting the greater improvement in RT for the trained groups (MT: $\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -799$ ms, SEM $= 79.7$ ms; BT: $\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -861$ ms, SEM $= 129.1$ ms) compared to the NT group ($\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -412$ ms, SEM $= 62.0$ ms). A-posteriori comparisons with Tukey's HSD confirmed that, while the trained groups differed significantly from the NT group ($p < 0.05$), the MT and BT groups did

Table 1. Mean reaction times and accuracy for each group in each condition. Standard errors are in parentheses.

Training group		Block 1 (baseline)	Block 2	
			feedback	no feedback
NT	reaction time/ms	3258 (143)	2890 (148)	2802 (150)
	accuracy/%	92 (1.5)	92 (1.2)	95 (1.2)
MT	reaction time/ms	3279 (113)	2433 (128)	2524 (135)
	accuracy/%	92 (1.2)	92 (1.1)	93 (1.2)
BT	reaction time/ms	3416 (188)	2481 (142)	2628 (145)
	accuracy/%	93 (1.5)	95 (1.2)	94 (1.8)

not differ from each other ($p = 0.931$). There was no main effect of feedback, and feedback did not interact with training.

To check that no group had a quasi-advantage in the ability to perform the task from the outset, baseline (block 1) RTs were compared by a one-way ANOVA with training as the grouping variable. No baseline differences were observed between groups for RTs, or any of the measures reported henceforth.

3.2 *Accuracy*
No significant main effects were found in the accuracy analysis, nor did the factors interact. Accuracy was high, however ($\bar{x} = 93\%$ correct overall, $\mathrm{SD} = 5.3\%$).

3.3 *Eye-movement recordings*
To properly understand the behavioural data obtained in the context of eye-movement control it is necessary to examine certain statistics of visual search and central-letter processing. In addition to the removal of practice, catch, anticipatory, and incorrect trials, trials in which the peripheral target was not fixated, the duration of the initial central gaze on the letter was <50 ms, and the central letter was not fixated within 4 fixations, were also excluded prior to analysis of the eye-movement data. Respectively, these criteria reduce the possibilities that participants were locating the target in peripheral vision, spending an insufficient time foveating the centre at the start of the trial, or searching the peripheral array first (even though they were specifically told not to do this). After these exclusions, an average of 36 trials contributed to each participant's cell means for the eye-movement measures taken. If a participant had less than 10 trials contributing to their cell mean for the baseline, feedback, or no-feedback blocks, he/she was removed from the subsequent eye-movement analysis. Loss of calibration among certain participants means that seven were excluded according to this criterion, three from the NT group and four from the MT group. Additionally, one participant was excluded (from the BT group) because of not completing the task properly. After removal of these participants, an average of 40 trials now contributed to the cell means. Although the eye-movement data were also analysed in terms of difference scores, the means in each condition are given in table 2.

3.4 *Overall visual-search performance*
The average number of fixations per trial ($\bar{x} = 8.31$ overall; $\mathrm{SD} = 1.82$) gives an indication of search efficiency. Analysis of the relative changes in these data revealed a significant main effect of training only ($F_{2,27} = 8.4$, $\mathrm{MSE} = 3.6$, $p = 0.001$), highlighting that the trained groups (MT: $\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -2.5$, $\mathrm{SEM} = 0.3$; BT: $\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -3.16$, $\mathrm{SEM} = 0.4$) make less fixations following training than the reduction afforded by practice alone (NT: $\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -0.8$, $\mathrm{SEM} = 0.23$). Tukey HSD a posteriori comparisons confirmed these differences (NT versus MT, BT: $p\text{s} < 0.05$; MT versus BT: $p = 0.54$).

Table 2. Summary statistics for the measures of eye movements taken. Means are shown for each group in each condition with standard errors in parentheses.

Training group	Eye-movement statistic	Block 1 (baseline)		Block 2 feedback		Block 2 no feedback	
NT	number of fixations per trial	9.6	(0.4)	8.9	(0.3)	8.8	(0.3)
	time to first target fixation/ms	1963	(137)	1702	(138)	1651	(134)
	initial central gaze duration/ms	473	(52)	397	(36)	455	(58)
	re-inspection duration/ms	186	(33)	143	(28)	185	(39)
	number of re-fixations per trial	1.1	(0.2)	0.7	(0.1)	0.9	(0.2)
MT	number of fixations per trial	9.4	(0.3)	6.9	(0.3)	6.9	(0.4)
	time to first target fixation/ms	1828	(226)	1197	(181)	1207	(180)
	initial central gaze duration/ms	643	(102)	608	(96)	664	(118)
	re-inspection duration/ms	146	(31)	187	(48)	133	(39)
	number of re-fixations per trial	0.7	(0.2)	0.7	(0.2)	0.6	(0.2)
BT	number of fixations per trial	10.2	(0.8)	6.8	(0.6)	7.2	(0.5)
	time to first target fixation/ms	1967	(173)	1132	(121)	1125	(135)
	initial central gaze duration/ms	399	(38)	539	(140)	472	(98)
	re-inspection duration/ms	178	(51)	163	(51)	203	(59)
	number of re-fixations per trial	1.0	(0.3)	0.7	(0.2)	0.9	(0.2)

Visual-search performance can also be assessed by looking at the time from commencement of the trial to fixation of the peripheral target. These data were extracted from the eye-movement recordings also, and, overall, participants fixated the target within an average of 1542 ms (SD = 593.7 ms). The relative-change analysis revealed a significant main effect of training only ($F_{2,27} = 6.7$, MSE = 234948, $p = 0.004$), with the trained groups (MT: $\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -625$ ms, SEM = 84.9 ms; BT: $\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -838$ ms, SEM = 110.7 ms) improving more than the NT group ($\overline{x_{\text{block 2}} - x_{\text{block 1}}} = -286$ ms, SEM = 39.0 ms. A-posteriori comparisons with Tukey's HSD revealed differences between the NT and BT groups only ($p = 0.004$); the comparison between the NT and MT groups narrowly failed to reach conventional statistical significance ($p = 0.078$), and the MT and BT groups did not differ ($p = 0.38$). This pattern of results complements the RT analysis, demonstrating the improved search efficiency of the trained groups.

3.5 *Visual scanning behaviour*

To relate the measures of visual-search performance outlined above to eye-movement patterns, typical scanpaths within a trial are plotted for two example participants (figure 2). Although detailed statistical analysis of these scanpaths is outside the scope of this article (see Foulsham and Underwood 2008 for a more comprehensive approach), they do reveal a number of interesting findings pertinent to the hypothesis. First, given the circular arrangement of stimuli in the periphery, participants commonly favoured a clockwise or counterclockwise eye-movement sequence (when untrained), as predicted. Such visual-search behaviour is similar to what has been previously described as a 'convex-hull' scanpath, where participants predominantly search the perimeter of an array of items making frequent forays into the centre (Findlay and Brown 2006). Given the layout of our stimuli, this is not so surprising; however, there were certain noteworthy characteristics of our participants' fixation sequences en route. Figure 2a (left panel) shows that, in trial 52 of the baseline block, subject 13 (from the NT group) commenced searching the periphery at target position 6, continuing up to position 8 before backtracking to position 7 to re-check the distractor there. After doing so, the original search did not resume from where it left off; instead, this participant moved over to the opposite side of the display and began to search in a clockwise order once more. An interesting observation of the search behaviour adopted in this trial is that,

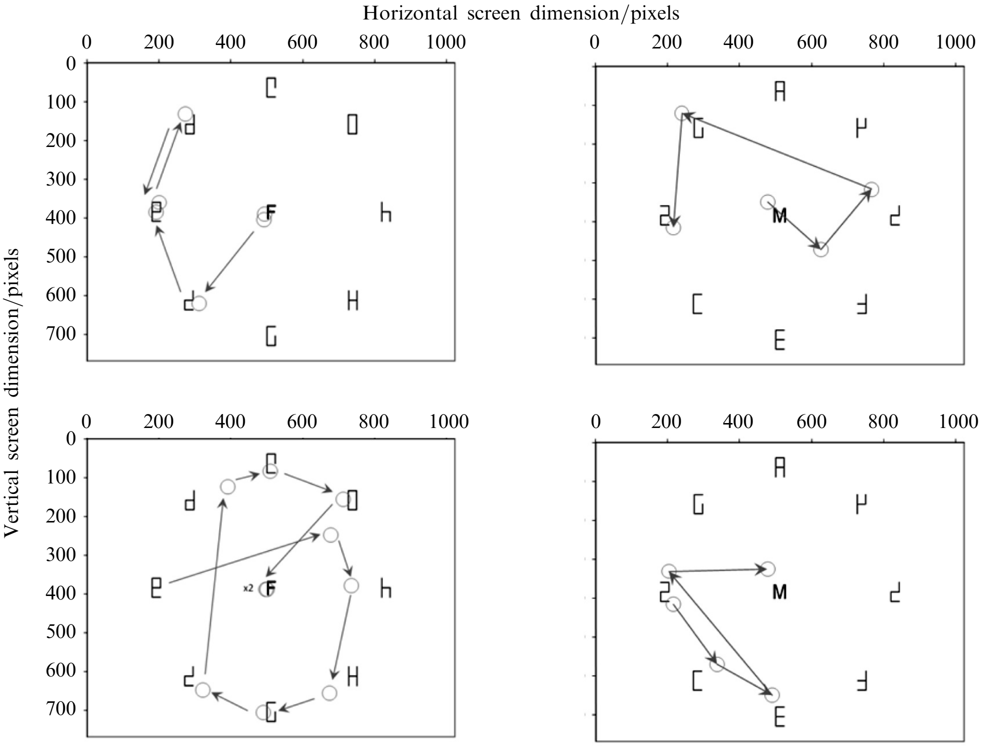


Figure 2a. The sequence of eye fixations made by an untrained participant (subject 13) in block 1 (left: trial 52) and block 2 (right: trial 187). Arrows indicate the order of fixations in the sequence not saccades per se. Each panel should be read from top to bottom, the first fixation in the bottom panels showing how the search continued from the last fixation in the top panels (in reality the sequence was continuous but is subdivided here to avoid clutter and overlap). Where two fixations are consecutive, overlapping and not easily discernible from subsequent return fixations '$\times 2$' is indicated on the figure. The x and y axes of each quadrant represent screen dimensions in pixels (1024×768, respectively).

once this subject reached the original location at which the search began, he/she remembered that the left hand side of the display had already been searched and continued up to the remaining segment that was yet to be inspected. This is an excellent example of an entirely exhaustive search where all possible regions were inspected before the target was found. As was frequently the case, the target fixation was the penultimate fixation of the trial, the final fixation being a re-fixation on the central letter.

Despite the minor practice effects of the NT group reported above, it can also be seen that, even towards the end of block 2, the same untrained participant failed to notice the predictable sequence of target presentation. This is nicely shown in figure 2a (right panel) where the participant began a counterclockwise search on the opposite side of the screen to the target and still passed over the target after it was eventually fixated, only backtracking to its location two fixations later. Indeed, surprisingly, when completing the debrief questionnaire, no subject explicitly reported guessing either the predictable order of target presentation or the symmetry rule which applied to the central letter. (Subsequent versions of this experiment have since been carried out with similar subject numbers, and only very occasionally did participants work out either of the strategies.)

The visual-search behaviour of the MT group at baseline was similar to that of the NT group. The example trial from subject 21 illustrates this (figure 2b, left panel). During block 2, however, the benefit of MT is apparent: Subject 21 commenced searching the

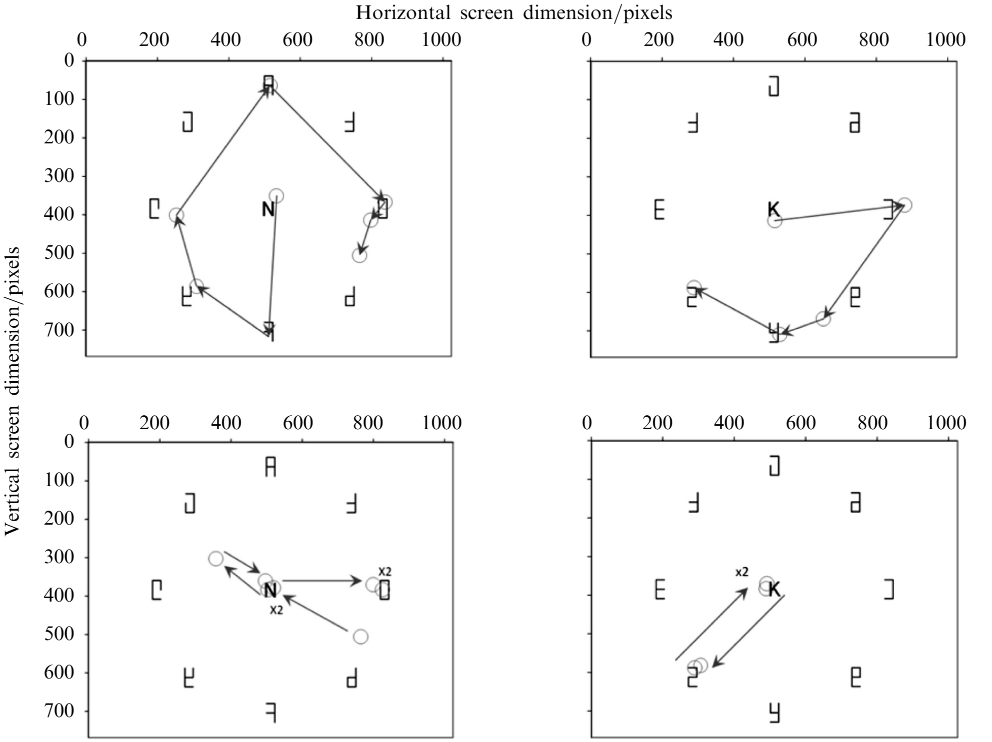


Figure 2b. The sequence of eye fixations made by a participant (subject 21) from the MT group in block 1 (left: trial 23) and block 2 (right: trial 152). Arrows indicate the order of fixations in the sequence not saccades per se. Each panel should be read from top to bottom, the first fixation in the bottom panels showing how the search continued from the last fixation in the top panels (in reality the sequence was continuous but is subdivided here to avoid clutter and overlap). Where two fixations are consecutive, overlapping and not easily discernible from subsequent return fixations '$\times 2$' is indicated on the figure. The x and y axes of each quadrant represent screen dimensions in pixels (1024×768, respectively).

periphery by returning to the target location of the previous trial, then promptly moved to the target location of the trial in hand (figure 2b, right panel). This strategy was quite common and is interesting because it indicates that subjects sometimes used the target location from the previous trial as a placeholder for the upcoming trial. This preference may suggest that, in our task, executing saccades to the exact location dictated by the MT strategy is more demanding than returning to the previous target position for guidance.

The final point of interest in the visual-scanning behaviour of the MT participants is that they often made consecutive re-fixations at the end of a trial, typically alternating between the target and the central letter several times before responding. This is important as it is in-line with the predictions of the main hypothesis. Eye movements of this type are exemplified in the bottom right panel of figure 2b.

3.6 *Central-letter processing: Initial central gaze duration*

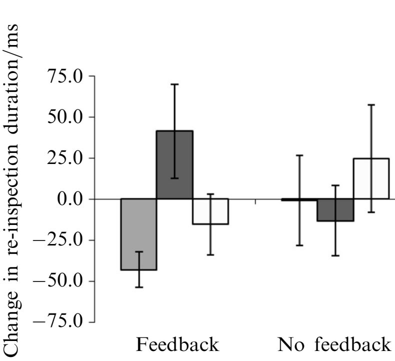
The summation of fixation durations for consecutive fixations made within the region of interest for the central letter, from the first fixation within this area until a saccade is made outside of it, gives an indication of how efficiently the central letter is initially processed. It also allows one to infer whether the MT strategy employed exerts any influence over this initial processing. These data were extracted from the eye-movement recordings, and, overall, the mean central gaze duration was 515 ms (SD = 227.8 ms). However, the relative change analysis revealed no significant differences, and is not reported further.

In an attempt to see whether other measures of initial letter processing yielded any significant results, both the mean number of fixations of which the central gaze duration consisted and the mean fixation duration for fixations contained within the central gaze duration were extracted and analysed. Again, however, the relative change analysis on these data revealed no significant effects. Therefore, one must conclude that neither training, feedback, nor a combination of these factors interacting affects the duration or amount of fixations made on the central letter.

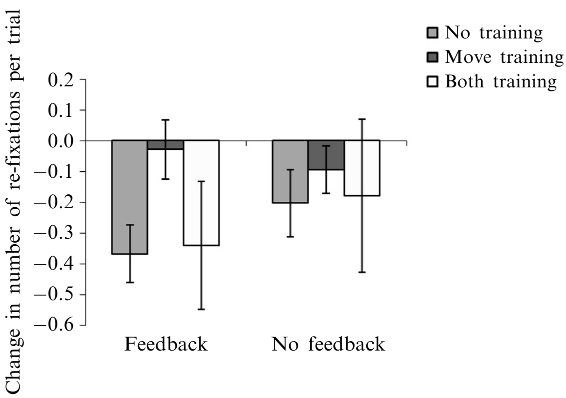
3.7 *Re-inspections of the central letter*

Apart from fixations classified as comprising the initial central gaze duration, any other fixation made on the central letter was identified as a re-fixation. For continuity, and to avoid any further data loss, we chose to calculate mean re-inspection durations (the average of re-fixation durations for all trials in an entire block, including those in which no re-fixation occurred). This approach was considered more logical than calculating the mean duration of re-fixations when they occurred, since we did not expect re-fixations for the NT and BT groups to be as numerous. Therefore, this measure keeps the number of trials contributing to each cell mean constant, favouring fair comparisons. However, it should be noted that the effects on re-inspection durations reported below remain for the more conventional measure of mean re-fixation. These data are not presented, however, because there were indeed too few trials contributing to certain participants cell means.

Overall the mean duration of re-inspections was 169 ms (SD = 128.5 ms). There was no main effect of training in the relative change analysis for this measure, nor was there a main effect of feedback. Crucially, however, these factors did interact ($F_{2,27} = 3.8$, MSE = 4029, $p = 0.036$). This interaction is charted in figure 3a and reflects the fact that the MT group has increased mean re-inspection durations, *but only when external visual feedback was presented*. In contrast, the provision of feedback did not increase the mean re-inspection durations of the other two groups; on the contrary, it seems to have reduced them. This suggests that feedback is beneficial unless trained on the Move centre in isolation. For the NT group, and to some extent the BT group, when feedback was available, the initial time spent processing the central letter seemed sufficient; therefore these groups showed a reduced need to return to it. When the MT group received feedback, however, the initial time spent processing the central letter seemed less than optimal; therefore these participants needed to re-inspect it for longer durations in order to respond correctly.



(a)



(b)

Figure 3. (a) Relative change from baseline in mean re-inspection durations for each group, across feedback conditions. (b) Reduction from baseline in the mean number of re-fixations per trial for each group, across feedback conditions. Error bars show ±1 SEM.

When feedback is not provided, however, this pattern changes: all groups now show more of a trend towards re-inspecting for comparable durations to those observed at baseline (ie 0 on the y axis of figure 3a). In fact, when feedback is not provided, the trend described above appears to reverse somewhat.

To assess these results, a posteriori tests were carried out. Two one-way ANOVAs were conducted, one comparing the differences between groups in the FB condition, and one comparing the differences between groups in the NFB condition. Only the first of these yielded a significant between-groups effect ($F_{2,27} = 4.7$, $\mathrm{MSE} = 4081$, $p = 0.018$), and Tukey HSD a posteriori comparisons showed that the difference in this analysis lies with the increase in mean re-inspection durations for the MT group and the decrease in mean re-inspection durations for the NT group ($p = 0.015$); the NT group did not differ from the BT group ($p = 0.609$), and the MT group did not differ from the BT group ($p = 0.150$). These analyses confirm that the MT group re-inspects the centre for longer than the NT group, but only in the FB condition.

The same analysis was conducted on the average number of re-fixations per trial (overall $\bar{x} = 0.83$, $\mathrm{SD} = 0.58$). There were no main effects, nor was the interaction significant. However, because we had reason to believe that the MT group would re-fixate the centre more regularly than the NT group, two independent-samples t-tests were carried out: the first on the difference between the NT and MT groups in the FB condition was significant ($t_{19} = -2.53$, $p = 0.021$); the second on the same groups in the NFB condition was not significant. This mirrors the re-inspection duration analysis (see figure 3a). Moreover, although all groups showed a slight decrease in re-fixations (figure 3b), a finding which is consistent with practice at the task, the MT group showed the smallest reduction. This, therefore, demonstrates that the re-inspection duration results described above are not the artifact of a trade-off where the longer re-inspections of the MT group are a consequence of this group making fewer re-fixations numerically.

4 Discussion

Several predictions were made from the outset regarding the consequences of training eye movements. It was hypothesised that isolated eye-movement training directed towards the Move centre of Findlay and Walker's model would in some way degrade the ability to process the centrally located letter, owing to competition between the need to fixate this item (or Fixate centre activity) and the urge to saccade towards the known location of the peripheral target (or Move centre activity). It was predicted that this effect would be exposed in one of two ways. First, it could appear as an effect on accuracy, with the MT group disengaging from the central letter before having fully processed it, therefore being uncertain of the correct response to make. Alternatively, MT participants might re-inspect the central letter more regularly for accuracy to be preserved. Evidence for the latter case was provided, not in the number of re-fixations per se, but in the re-inspection durations. The data confirm that, although all groups showed comparable processing time on the central letter in the first instance (reflected in the initial central gaze duration measure), the MT group alone failed to process the item adequately within this time, needing to re-inspect it for longer in order to respond correctly.

On the surface, it appears that directing eye-movement training towards the Move centre of Findlay and Walker's model is beneficial: it improves visual-search performance in terms of reaction times and overall search efficiency, desirable goals for any eye-movement training strategy; yet conversely, more subtle detrimental effects on the processing of individually fixated items can be missed. It is necessary, however, in light of there being no differential effect of training on the initial processing of the central letter, to relate the suggested competition between the Move and Fixate centres to some form of covert attention shift towards the saccade target before the eyes move.

This idea can be supported by considerable evidence about covert attention (eg Engel 1971; Eriksen and Hoffman 1972; Koivisto et al 2004; Motter and Holsapple 2007; Posner et al 1980). Koivisto et al (2004) used an inattentional blindness paradigm to show that, when participants fixate the central region of a display and orient covertly to peripheral targets, they fail to notice an unexpected stimulus, even when it is always presented centrally at the point of fixation. A similar process of 'looking but failing to see' may well account for the present results. However, because in our task participants were not explicitly instructed to keep their eyes fixed at the centre, an interesting conclusion emerges: the delay between a covert shift of attention and a proceeding saccade can vary according to task demands, even when subjects are free to move their eyes. Whether the time course of covert shifts can vary is somewhat controversial in the literature; nevertheless *spatial selection* in Findlay and Walker's model provides a component which could potentially account for the effects observed here (this feature of Findlay and Walker's framework operates much like the traditional spotlight or zoom lens models of attention, selectively enhancing a spatially restricted region before the eyes move). Further research with the present paradigm, using variable stimulus onset asynchronies for the peripheral array, or a gaze-contingent window outside of which peripheral information is obscured, would help address these issues. At present, these remain avenues for future research.

The finding of increased re-inspection durations for the MT group provides an explanation why some previous attempts to train eye movements may not have had the desired outcomes (Chapman et al 2002; Donovan et al 2005; Quevedo et al 1999). Moreover, it should raise awareness amongst researchers when developing eye-movement training regimes for use in applied settings, because it suggests that the emphasis often placed upon moving the eyes (eg Mills 2005; UK Department for Transport 2007) may be misplaced. Indeed, we have shown that the most effective way to employ visual training is to concentrate efforts towards the Fixate centre *as well as* the Move centre. When this is done (as demonstrated with the BT group in the present experiment) the deficit associated with MT alone is abolished. The training directed at the Fixate centre, employed by the BT group, seems to reduce the processing demands of the central letter despite its appearance remaining unchanged. This is in line with similar reports of higher influences on the Fixate centre when stimulus characteristics are kept constant (Gould 1973; Zingale and Kowler 1987).

However, the finding of longer re-inspection durations for the MT group was only the case when visual feedback was presented in-between trials informing participants of the accuracy of their responses. When an uninformative transient grey mask was presented after each trial, irrespective of the response, participants given MT no longer showed any evidence of competition between the Move and Fixate centres detracting from the ability to process the central letter. One potential reason for this is that, when executing the highly coordinated sequence of eye movements and stimulus processing required, the MT group is better able to carry out the task when they can internally regulate error monitoring. External feedback therefore might lead to a bottleneck in a capacity-limited system (see Pashler 1994) where the competing demands to remember the sequence of eye movements required, the response to be made to the central letter, and to process the feedback mask, overload cognitive resources. As a result of this conflict, it is the initial processing of the central letter which is hindered for the MT participants, a problem which is remedied by looking back towards the letter for longer durations. This does not occur for the NT and BT groups, however, because for these participant groups one of the factors causing the bottleneck is removed: the NT group does not have a sequence of eye movements to remember, and the difficulty of processing the central letter is reduced for the BT group. As a result, the feedback mask has an interfering effect on the MT group only, while it assists the NT and BT groups.

Interestingly, previous research has shown that, when a voluntary saccade is being planned, oculomotor capture from an abrupt onset is likely (Theeuwes et al 1999), whereas this capture does not occur when the task is to remain fixated (Tse et al 2002). Although the feedback masks we used were global transients, it may be that they cause a similar process of interference for the MT group when voluntarily executing saccades dictated by the training scanpath. This may not occur for the other two groups, however, because competition between the Move centre and Fixate centre is weaker, and there are fewer cognitive demands causing a bottleneck.

The argument presented above suggests that the MT group prefers to internalise error monitoring. However, how might this process be carried out? It is feasible that, when feedback is not provided, MT participants have a higher likelihood of generating feedback Error Related Negativity (fERN—Holroyd et al 2006), a frontal lobe ERP component associated with evaluating the outcomes of actions in the absence of external feedback. If this is the case, the higher and less specified levels of Findlay and Walker's model should be revised to take account of this possibility when training eye movements.

The pattern of results observed suggests that training directed at *both* the Move *and* Fixate centres of Findlay and Walker's model is advisable. Although MT in isolation can be beneficial, this was only the case when visual feedback was not pertinent to the task at hand. Therefore, because, particularly in applied settings, interaction with the environment and awareness of visual reinforcement is vital, it seems less likely that eye-movement training directed solely at the Move centre will be helpful. Clearly, however, there are big differences between the experimental task we used and 'real life' scenarios; we controlled exactly the characteristics of the stimuli, therefore knew precisely what training strategies to advise. Nevertheless, despite the differences between this study and applied contexts, it is evident that additional focus from domain-specific experts should be given to the processing of fixated items, in concert with assisting in the ability to visually locate them which has been the predominant drive in recent years. To refer back to the example of the 'look but fail to see' accident causation factor (Brown 2002) in driving, implementing visual training that simultaneously tackles the problems of locating *and* processing important objects may be as simple as advising drivers to fixate for longer. For example, "look right CHECK, look left CHECK, then right again" (UK Department for Transport 2007).

Acknowledgments. We would like to thank Peter Chapman, Thomas Foulsham for useful discussions, the Economic Social Research Council for funding this work, and two anonymous reviewers for their helpful comments on an earlier draft of this manuscript.

References

Brown I, 2002 "A review of the 'look but fail to see' accident causation factor" *Behavioural Research in Road Safety* **11** 116 – 124

Chapman P R, Underwood G, Roberts K, 2002 "Visual search patterns in trained and untrained novice drivers" *Transportation Research Part F—Traffic Psychology and Behaviour* **5** 157 – 167

Clark D, Ward P, Truman W, Bartle C, 2004 "An in-depth case study of motorcycle accidents using police road accident files" *Proceedings of the 14th Seminar on Behavioural Research in Road Safety* (London: Department for Transport) pp 5 – 20

Donovan T, Manning D J, Phillips P W, Highman S, Crawford T, 2005 "The effect of feedback on performance in a fracture detection task" *Progress in Biomedical Optics and Imaging (SPIE)* **6** 79 – 85

Engel F L, 1971 "Visual conspicuity, directed attention and retinal locus" *Vision Research* **11** 563 – 575

Eriksen C W, Hoffman J E, 1972 "Temporal and spatial characteristics of selective encoding from visual displays" *Perception & Psychophysics* **12** 201 – 204

Findlay J M, Brown V, 2006 "Eye scanning of multi-element displays: I. Scanpath planning" *Vision Research* **46** 179 – 195

Findlay J M, Walker R, 1999 "A model of saccade generation based on parallel processing and competitive inhibition" *Behavioral and Brain Sciences* **22** 661 – 721

Foulsham T, Underwood G, 2008 "What can saliency models predict about eye movements? Spatial and sequential aspects of fixations during encoding and recognition" *Journal of Vision* **8**(2:6) 1 – 17
Godijn R, Theeuwes J, 2002 "Programming of endogenous and exogenous saccades: Evidence for a competitive integration model" *Journal of Experimental Psychology: Human Perception and Performance* **28** 1039 – 1054
Gould J D, 1973 "Eye movements during visual search and memory search" *Journal of Experimental Psychology* **98** 184 – 195
Hajcak G, Holroyd C B, Moser J S, Simons R F, 2005 "Brain potentials associated with expected and unexpected good and bad outcomes" *Psychophysiology* **42** 161 – 170
Herslund M B, Jorgensen N O, 2003 "Looked-but-failed-to-see-errors in traffic" *Accident Analysis and Prevention* **35** 885 – 891
Holroyd C B, Hajcak G, Larsen J T, 2006 "The good, the bad and the neutral: Electrophysiological responses to feedback stimuli" *Brain Research* **1105** 93 – 101
Itti L, Koch C, 2000 "A saliency-based search mechanism for overt and covert shifts of visual attention" *Vision Research* **40** 1489 – 1506
Koivisto M, Hyona J, Revonsuo A, 2004 "The effects of eye movements, spatial attention, and stimulus features on inattentional blindness" *Vision Research* **44** 3211 – 3221
Logan G D, 1996 "The CODE theory of visual attention: An integration of space-based and object-based attention" *Psychological Review* **103** 603 – 649
Martens M H, Fox M R J, 2007 "Do familiarity and expectations change perception? Drivers' glances and response to changes" *Transportation Research Part F—Traffic Psychology and Behaviour* **10** 476 – 492
Mills K, 2005 *Disciplined Attention: How to Improve Your Visual Attention When You Drive* (London: Profile Books)
Morrison R E, 1984 "Manipulation of stimulus onset delay in reading—evidence for parallel programming of saccades" *Journal of Experimental Psychology: Human Perception and Performance* **10** 667 – 682
Motter B C, Holsapple J, 2007 "Saccades and covert shifts of attention during active visual search: Spatial distributions, memory, and items per fixation" *Vision Research* **47** 1261 – 1281
Munoz D P, Wurtz R H, 1993 "Fixation cells in monkey superior colliculus. 1. Characteristics of cell discharge" *Journal of Neurophysiology* **70** 559 – 575
Munoz D P, Wurtz R H, 1995a "Saccade-related activity in monkey superior colliculus. 1. Characteristics of burst and buildup cells" *Journal of Neurophysiology* **73** 2313 – 2333
Munoz D P, Wurtz R H, 1995b "Saccade-related activity in monkey superior colliculus. 2. Spread of activity during saccades" *Journal of Neurophysiology* **73** 2334 – 2348
Pashler H, 1994 "Dual-task inference in simple tasks—data and theory" *Psychological Bulletin* **116** 220 – 244
Posner M I, Snyder C R R, Davidson B J, 1980 "Attention and the detection of signals" *Journal of Experimental Psychology: General* **109** 160 – 174
Quevedo L, Sole J, Palmi J, Planas A, Soana C, 1999 "Experimental study of visual training effects in shooting initiation" *Clinical Experimental Optometry* **82** 23 – 28
Reichle E D, Pollatsek A, Fisher D L, Rayner K, 1998 "Toward a model of eye movement control in reading" *Psychological Review* **105** 125 – 157
Theeuwes J, Kramer A F, Hahn S, Irwin D E, Zelinsky G J, 1999 "Influence of attentional capture on oculomotor control" *Journal of Experimental Psychology: Human Perception and Performance* **25** 1595 – 1608
Tse P U, Shienberg D L, Logothetis N K, 2002 "Fixational eye movements are not affected by abrupt onsets that capture attention" *Vision Research* **42** 1663 – 1669
UK Department for Transport, 2007 "*Think Bike" Campaign* (London: UK Department for Transport)
Veen V van, Holroyd C B, Cohen J D, Stenger V A, Carter C S, 2004 "Errors without conflict: Implications for performance monitoring theories of anterior cingulate cortex" *Brain and Cognition* **56** 267 – 276
Zingale C M, Kowler E, 1987 "Planning sequences of saccades" *Vision Research* **27** 1327 – 1341

ISSN 0301-0066 (print) ISSN 1468-4233 (electronic)

PERCEPTION

VOLUME 37 2008

www.perceptionweb.com