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Acta Psychologica 127 (2008) 398–406

acta psychologica

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Simultaneous processing of visual information and planning of hand movements in a visuo-manual search task

Hanneke Liesker *, Jeroen B.J. Smeets, Eli Brenner

Faculty of Human Movement Sciences, Vrije Universiteit, Van der Boechorststraat 9, 1081 BT Amsterdam, The Netherlands

Received 1 February 2007; received in revised form 9 July 2007; accepted 26 July 2007
Available online 11 September 2007

Abstract

When searching for a target with eye movements, saccades are planned and initiated while the visual information is still being processed. If hand movements are needed to perform a search task, can they too be planned while visual information from the current position is still being processed? To find out we studied a visual search task in which participants had to move their hand to shift a window through which they could see the items. The task was to find an O in a circle of Cs. The size of the window and the sizes of the gaps in the Cs were varied. Participants made fast, smooth arm movements between items and adjusted their movements, when on the items, to the window size. On many trials the window passed the target and returned, indicating that the next movement had been planned before identifying the item that was in view.

PsychINFO classification: 2323; 2330

Keywords: Visual perception; Movement; Human

1. Introduction

In everyday life, we frequently find ourselves looking for a specific object or item in a visual scene. For instance, searching for our keys on our desk, or a friend in a crowded place. Visual search experiments study this behaviour. In such experiments displays consisting of a number of separate items are presented. Participants are instructed to search for a pre-defined target among a varying number of distracter items (Treisman & Gelade, 1980). If the target is hard to detect, because it is inconspicuous or because the items can only be discriminated if they fall within the fovea (Carpenter, 1988), eye movements are needed to find the target and participants take a long time to detect it. In such search tasks, participants alternately fixate for some time and make saccades towards new positions.

Strategies in visual search have been studied by taking measures of fixation duration. Mocharnuk (1978) concluded that fixation duration reflects the amount of information that is processed. But the fixation can be expected to reflect both the visual processing time and the oculomotor latency: the time the oculomotor system takes to initiate the next eye movement (Moffitt, 1980). The time needed to initiate the next eye movement presumably varies between 150 and 200 ms (Becker & Jürgens, 1979; Joiner & Shelhamer, 2006), while the time needed for analysing the foveal target can be as short as 100 ms (Eriksen & Eriksen, 1971).

Hooge and Erkelens (1996) examined whether the result of the analysis of the foveal target is used to plan the next eye movement. If so, then the process of analysing the foveal target would have to be finished before starting to plan the next eye movement. If not, then the analysis of the foveal target may continue while the next eye movement is being planned or even executed. They designed their stimuli in such a way that only one item could be analysed during a period of fixation, so that participants had

* Corresponding author. Tel.: +31 20 5982627; fax: +31 20 5988529.
E-mail address: h.liesker@fbw.vu.nl (H. Liesker).

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doi:10.1016/j.actpsy.2007.07.008

to make eye movements to check each of the items. The stimuli consisted of seven items positioned equidistantly on a circle. In their experiment, fixation durations ranged between 150 and 450 ms, depending on the discriminability of the target. Participants fixated the items one at a time, scanning the stimulus circle systematically in a clockwise or counter-clockwise direction. On 5–55% of the trials (depending on the condition of the task and on the participant) participants made additional saccades after fixating the target. They recognized the target, but too late to cancel the following eye movement, so they made another saccade before returning to the target. Hooge and Erkelens concluded that the foveal target is still being analysed while the next eye movement is planned. Does this also hold for hand movements?

It is not evident that when making hand movements to find a target, participants will also pass the target and return to it, recognizing it too late to cancel the following hand movement. Overvliet, Smeets, and Brenner (2007) studied participants performing haptic search tasks. In their experiments, participants had to find a target among other items positioned in a straight line by moving their fingertips over the items to feel them. They found that participants never passed the target. So, when hand movements are needed to identify a tactile target, the hand does not move on before the tactile information has been fully processed.

There is quite some literature on the relation between eye and hand movements. In everyday tasks the eyes often move ahead of the hand. For instance, when making tea or preparing sandwiches participants fixate an object before they manipulate it (Land & Hayhoe, 2001). Hand and arm movements have longer latencies and movement times than saccades (Bekkering, Adam, Kingma, Huson, & Whiting, 1994; Neggers & Bekkering, 1999; Prablanc, Echailler, Komilis, & Jeannerod, 1979; Sailer, Eggert, Ditterich, & Straube, 2000), and in everyday tasks the eyes make more movements than the hand (Ballard, Hayhoe, Li, & Whitehead, 1992). Moreover, eye movements normally influence what one sees, whereas hand movements normally do not affect vision. Because eye movements have lower costs in both energy and time and the hand and arm have more inertia to overcome than the eyes, one can afford to make more incorrect eye movements, and the hand and eyes do not need to make the same movements. But as the hand is slower, there is more benefit of starting early when making hand movements. We examine whether movement planning and visual information processing only occur in parallel for eye movements.

To find out we designed an experiment that was a variation of the one done by Hooge and Erkelens. In our experiment participants also had to find an O in a circle of Cs. The items were projected on a graphical tablet (see Fig. 1). Participants could always see the item positions, but had to move a pen across the graphical tablet to move a window through which they could see the actual shape of the items. To investigate the influence of the field of view

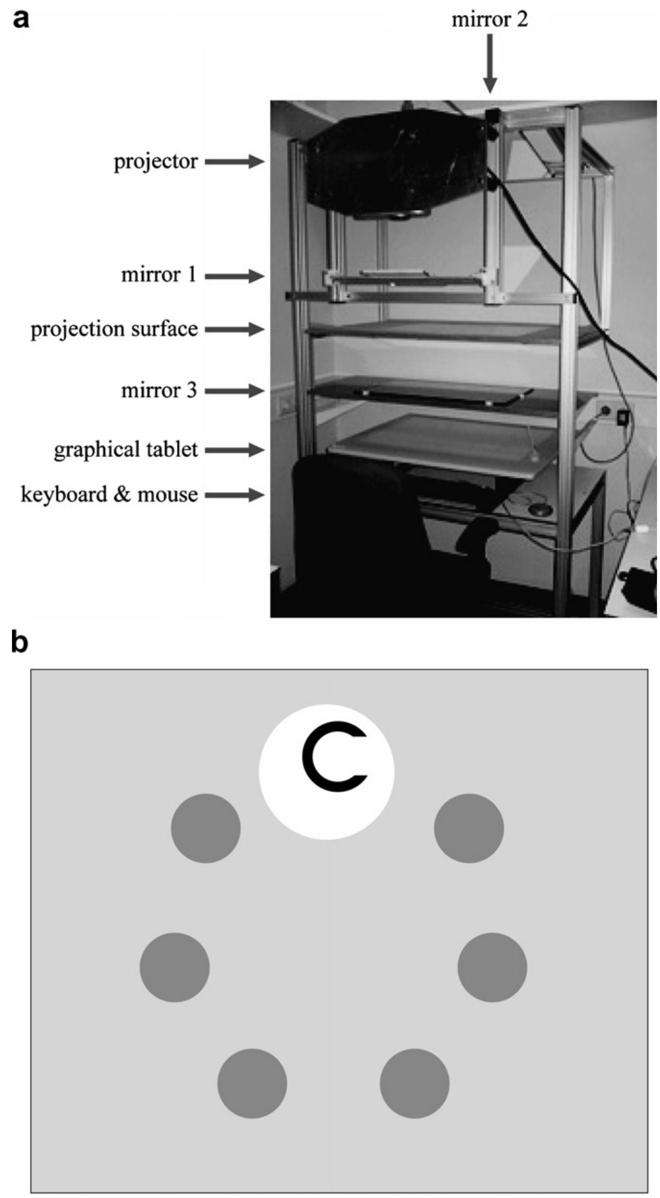

Fig. 1. a: The experimental set-up. The stimulus was projected via two mirrors onto a projection surface. Participants saw this stimulus via a third mirror, making it appear to coincide with the surface of a graphical tablet. Participants moved a pen over the graphical tablet and indicated that they had found the target by pressing the space bar on the keyboard or clicking the mouse button. b: The stimulus. The dark grey disks indicate the item positions. The white circle is the window that the participant can move over the items and through which an item, here with a large gap, is visible.

and of the discriminability of the target, we systematically varied the window size and the size of the gaps in the Cs. Thus, our search task can be compared to visual search with eye movements under conditions for which the items are visible eccentrically but the gaps are not. The main difference is that in our task the participants had to move both their eyes and hand accurately in order to find the gap. If participants regularly pass the target and return to it we can conclude that they have dwelled on items for less time than is needed to detect the target before planning the next movement, so movements are planned while visual information is still being processed. If participants never pass the target and return to it we can conclude that the next movement is only initiated after the visual information has been processed.

2. Methods

2.1. Participants

Twelve participants, seven women and five men, aged between 24 and 41 years, participated in this experiment. All participants had normal or corrected to normal vision. Two of them were authors (HL and JS) and were familiar with the goals of the experiment. One of them, HL, had some practice with the task because she tested the equipment and conditions before the experiment.

2.2. Apparatus

Participants were seated in a chair in the set-up shown in Fig. 1a. The stimulus was generated by an Apple Power Mac G4 (resolution 1024×768 pixels for a 57.5×43 cm image; refresh rate 85 Hz) and projected by a video projector (Boxlight), via mirrors, onto a back projection screen. Participants looked downwards into a mirror (mirror 3 in Fig. 1a) where they saw the reflection of the projected image that exactly coincided with the felt surface of the graphical tablet (Wacom Digitizer II, sampling frequency 200 Hz). Participants adjusted the height of the chair so that they could see the whole image in the mirror and move the pen comfortably over the graphical tablet. The distance from the eyes to the projection of the image was about 55 cm, so that 1 cm corresponds with about 1° of visual angle. Participants put their non-dominant hand on either the keyboard or the mouse, which were both positioned under the graphical tablet (see Fig. 1a). They indicated that they had found the target by pressing the keyboard's space bar or clicking the mouse button.

2.3. Procedure

At the beginning of each trial a dark grey disk (radius 2 cm) appeared at the centre of the bright grey image on the projection screen. Participants were instructed to place the tip of the pen on this disk, using their dominant hand. Once they did so, the seven item positions appeared as 2 cm radius dark grey disks, positioned at equal distances on a 12 cm radius circle around the centre of the screen. At the same time the central disk was replaced by a circular window (size varied between conditions) showing a white background. By moving the pen over the graphical tablet participants moved the window across the background, with a delay between moving the pen and the change in appearance in the image of about 60 ms. This delay stimulated participants to start moving early. Whenever the window moved over an item, the part of the item that was within the window was visible as a black drawing on the white background.

The items were six non-target Cs and one target O. The task for the participants was to find the O as quickly as possible. The outer radius of each item (C or O) and that of the grey disks indicating the item positions was 2 cm. The inner radius of all items was 1.3 cm. The participants were instructed not to lift the pen from the tablet during the task. They were instructed to find the target and then press the space bar on the keyboard or click the mouse button (whichever they preferred), while the pen was on the target, to indicate that they had found the target. Thus, if they moved beyond the target they had to move back before pressing the space bar or mouse button. Subsequently, the starting position for the next trial was presented. Before starting the experiment, the participants were given seven practice trials. We varied the size of the window (radius 4, 2 or 1 cm) and of the gaps in the Cs (width 1.16, 0.58 or 0.29 cm; the latter two were also used in the experiment by Hooge and Erkelens). The position of the gap in the C was chosen at random from the top, bottom, left and right.

The different window sizes and gap sizes were presented in separate blocks of trials. So, for each participant the experiment consisted of 3 (window size) $\times$ 3 (gap size) = 9 blocks. Each block consisted of 21 trials, in which each of the seven possible target positions appeared three times, in random order. Participants could take a break between blocks. Block order was randomised across participants. During the experiment the x and y positions of the tip of the pen on the graphical tablet were collected at 200 Hz. Trials in which the tip of the pen was not positioned on the target when participants gave their response, were considered invalid trials and were not included in the data analysis.

2.4. Data analysis

Data were analysed using MATLAB. The x and y position data were first cut into functionally different segments. The first part of each trial, from when participants put the tip of the pen on the dark grey disk in the centre of the stimulus circle until the pen (which moved the window) reached the first item, was excluded from further analysis because during that time there was no information to process. The rest of the positional data was split into sequences of two functionally different parts: (1) the parts in which an item was (entirely or partly) visible inside the window, and (2) the parts in which no item was visible inside the window. The first were called "view segments", the second "movement segments". The mean velocity during, and the mean duration of, these view and movement segments were determined, as was the average velocity profile within each segment. In the large window condition there are no movement segments because from the moment the first item is visible there is always at least one item (entirely or partly) visible: the next item enters the window before the present item has left the window. When two items were (partly) visible the moment that the centre of the window crossed the midline between the two items was considered as the transition between the two view segments.

Return movements are movements back to the item that has just been seen. A movement was considered to be a return movement if the participant left an item's view segment (to the next movement segment in the small or medium window condition or to the next view segment in the large window condition), and then immediately returned to the item. Repeated measures analyses of variance (ANOVAs) were conducted using SPSS software, with window size (3) and gap size (3) as independent variables and search time, duration of the view segments, duration of the movement segments, velocity of the view segments and velocity of the movement segments as dependent variables. For the figures, values were averaged and standard errors were calculated across participants.

3. Results

There were 2268 trials in total, 76 of which were rejected as invalid trials (false alarms; the tip of the pen was not positioned on or close to the target when the key or button was pressed). There were no misses (no response given).

Fig. 2 shows trajectories of the pen while the participants were searching for the target on several trials. The search paths show that participants do not start searching at a fixed item position. Participants sometimes moved in a clockwise direction and sometimes in a counter-clockwise direction around the circle of items. The small window forces participants to use a different strategy from the one in the large and medium window conditions: they make circular movements on each item in order to see whether the item is the target or a distracter. There is an understandable tendency for the movements to be slower and more accurate for the small window and gap size: thick lines indicate that the movement is slow. These examples also show that participants sometimes moved on from the target to the next item, and then returned to the target. This is clearly visible in the examples of the search paths for the large window condition. Such return movements occurred in 37% of the trials with the large window, in 13% of the trials with the medium-sized window and never in the trials with the small window. Eleven of the 12 participants show these return movements. Before analysing these return movements, we will first take a better look at the timing of the movements.

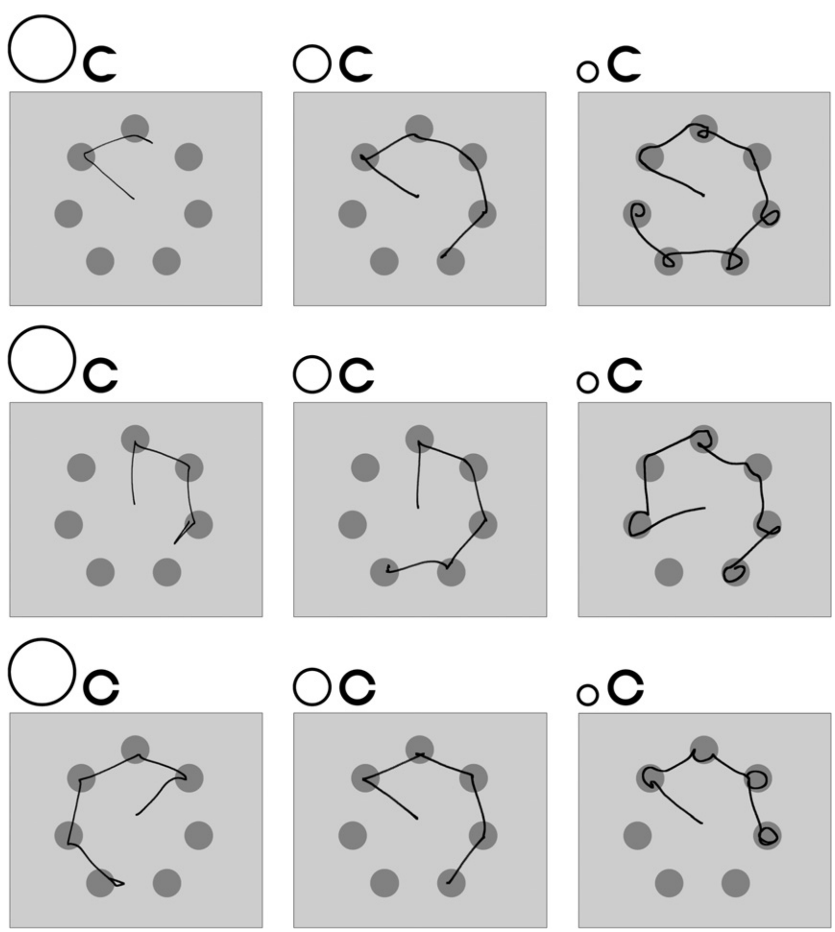

Fig. 2. Typical examples of participants' search paths, for each of the nine conditions. The open circle at the top left of each panel shows the window size and the C shows the gap size. Thicker lines indicate slower movements.

As was to be expected, the search time was longest when the window was small (Fig. 3. $F(2,22) = 233.884, p < 0.001$). The search time is also slightly longer when the gap size is small ($F(2,22) = 3.944$, $p < 0.05$), and there is a significant interaction between window size and gap size ($F(4,44) = 6.716, p < 0.001$). The latter two effects are probably mainly due to the fact that the search time for the small gap size is particularly long in the small window size condition.

In order to see whether the changes in search time are due to changes in the time spent moving between the items or to changes in viewing time, we split the x and y position data up into view segments and movement segments. Fig. 4 shows that participants spent most of their time in view segments. The mean duration of the view segments depended on the window size ($F(2,22) = 166.224$, $p < 0.001$) as well as the gap size ($F(2,22) = 8.672, p < 0.005$). The mean duration of the movement segments was longer for the smaller window size ($F(1,11) = 131.226$, $p < 0.001$) and was independent of gap size. The fact that participants take longer to move with a small window than with a medium-sized window is not at all surprising, because the movement must cover a longer distance for the smaller window, and because movements with a smaller window require better accuracy.

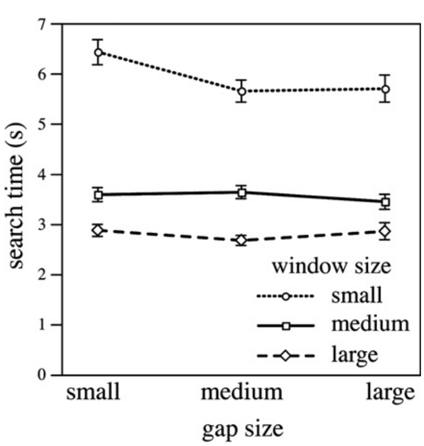

Fig. 3. Average search times for the three gap size and three window size conditions. Error bars indicate the standard error of the mean across participants.

Fig. 5 shows that the mean velocity during the view segments is higher for the largest window size ($F(2,22) = 40.533$, $p < 0.001$). The mean velocity during the movement segments does not depend on the window or gap size. Fig. 6 shows the average velocity profiles within each segment. These velocity profiles are symmetrical. Despite the smaller window size, the items remained visible for a longer time for the medium-sized window (634 ms) than for the large window (469 ms), because the window was moved more slowly. The velocity profile for the small window has a different shape. In this condition, the hand keeps moving at about 11 cm/s as it makes circular movements within each item to find the gap (see circular paths within items in Fig. 2). Thus for the small window participants had a longer path to cover: they had to cover the rim of the items (the C or O). Since there were four possible orientations of the Cs, on average participants had to cover half of the rim of the items to find the gap, which is a distance of about πr (depending on the exact path). In the other conditions, participants only needed to cross the items, which is a distance of $2r$. The ratio between these distances ($\pi/2 \approx 1.5$) could at least partly explain the twofold difference in duration between view segments for the medium-sized and the small window. However, the whole movement pattern is different for the small window, because the window being smaller than the items makes the task different in the small window condition. The fact that participants had the same mean velocity during movement segments for the medium-sized window as for the small window is therefore far from self-evident because the velocity profile for the small window had a very different shape.

The results in Figs. 3–5 are averaged over the whole search sequence. However, during the sequence the probability that the next item is the target increases with each item, so the search strategy might change during the search.

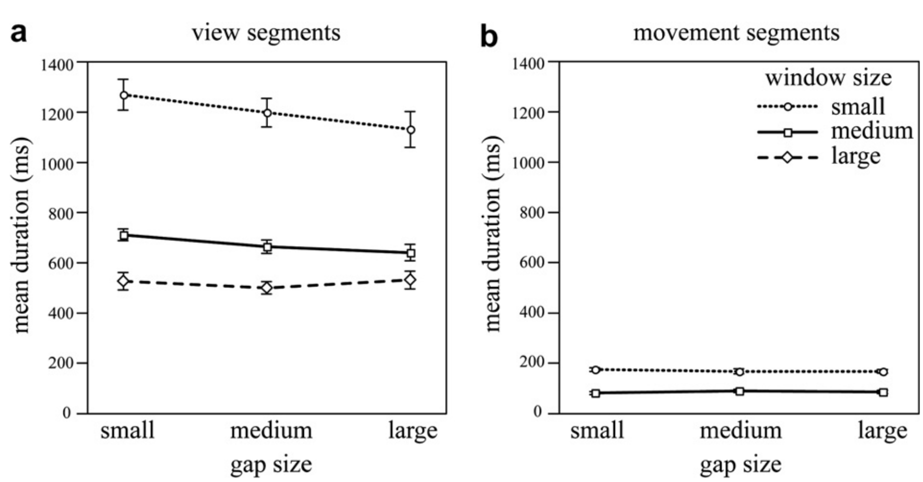

Fig. 4. Mean durations of the two types of segments for the nine conditions. Note that in the large window condition there were no movement segments.

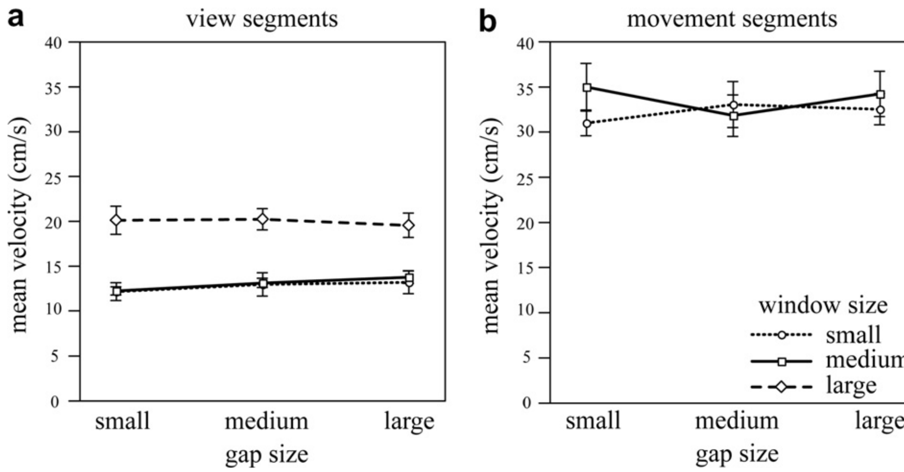

Fig. 5. Mean velocities during the two types of segments. Note that in the large window condition, there were no movement segments.

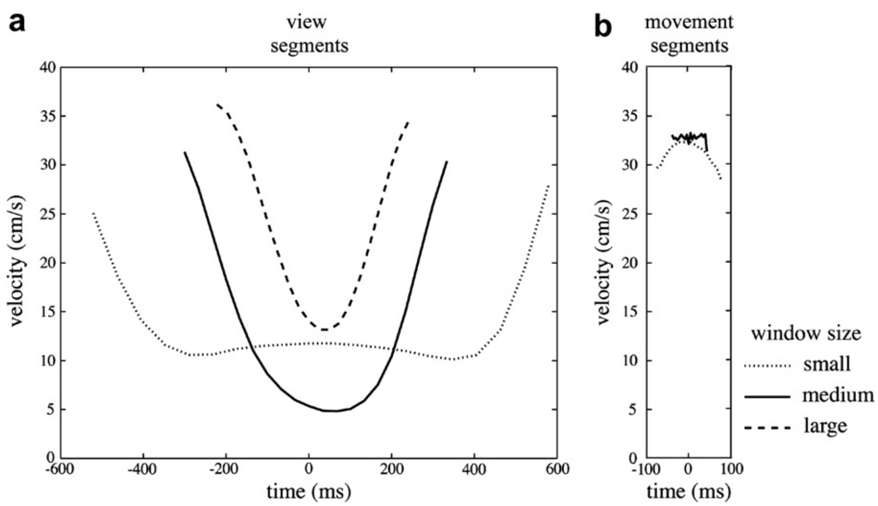

Fig. 6. Average velocity profile per visible item for the three window sizes. Velocity profiles as a function of relative time were averaged and plotted as a function of the average time, centred at the moment that 50% of the view (a) or movement (b) segment had elapsed. Note that in the large window condition there were no movement segments.

Fig. 7 shows the mean durations of the consecutive view and movement segments. The mean duration (Fig. 7a and b) differs for the three window sizes for the view segments, and for the two window sizes for the movement segments, as already shown in Fig. 4. For the second to the sixth item the viewing time increased slightly with every item. The view segments were a bit shorter for the last item and longer for the first item.

Is there a relation between the number of return movements and the probability that the item is the target? Fig. 7c shows the percentage of return movements for each of the items when it was the target. For item 7 there were no return movements. This was the last item, so participants knew that it had to be the target. The movement time and viewing time were also shortest in this case (see Fig. 7a and b). This might be explained by the fact that participants do not need to plan a following movement and they are ready to press the space bar, because they know that this will be the target. The decrease in the percentage of return movements from segment 2 to 6 in Fig. 7c may be related to the increase in durations for the view segments in Fig. 7a. After every item, participants' expectation that the next item would be the target increased, so they increased the durations of the view segments. As a result they did not pass the target on as many trials so there were fewer return movements. Fig. 7d shows the relation between the length of the view segment and the number of return movements. This relation is a kind of speed-accuracy trade-off. The fits for the two window sizes are parallel but there is an offset between them. This offset probably reflects the fact that our criterion for defining a return movement means that a smaller overshoot and return movement will be classified as a return movement for the medium window size than for the large window size.

Do participants who show shorter view segments also show more return movements? Do trials characterized by

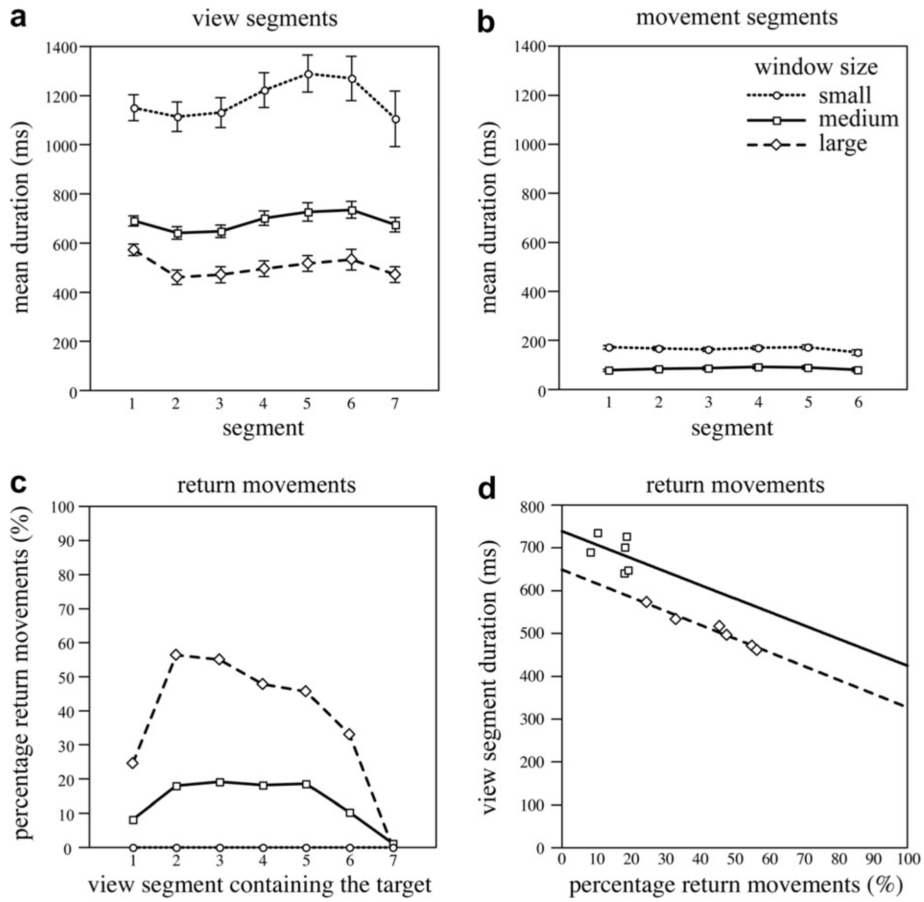

Fig. 7. Analysis of consecutive segments. a and b: Mean duration of consecutive segments. Note that in the large window condition there was always an item (entirely or partly) visible, so the whole trial consisted of view segments. The number of trials included decreases with segment number because the trial ends as soon as the target is found. c: Percentage of return movements when the item that was visible on that segment was the target. In the small window condition there were no return movements. d: Mean duration of the view segment containing the target as a function of the percentage of return movements. Each point represents a different position of the target in the sequence.

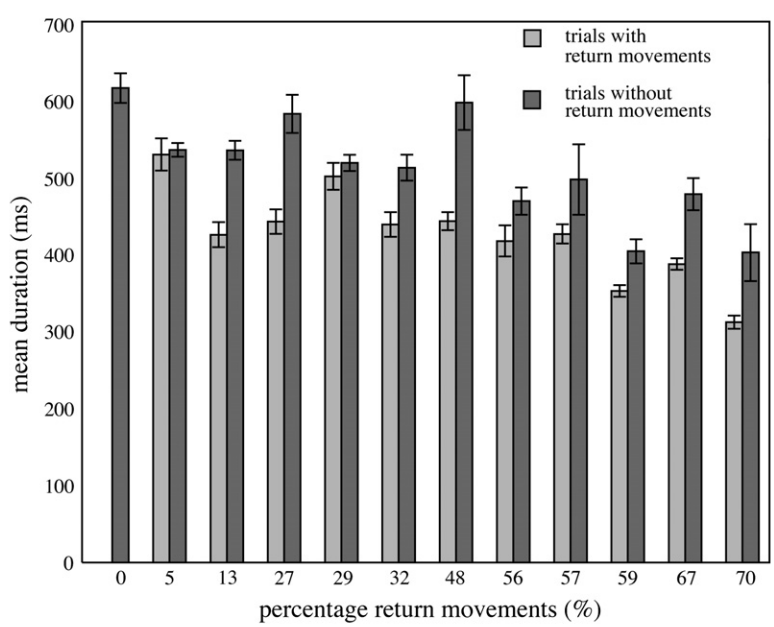

Fig. 8. Brighter bars: trials with return movements, the duration of the view segment containing the target before the overshoot and return movement. Darker bars: trials without return movements, the duration of the last view segment before the one containing the target. Mean duration of these view segments, for each participant, in the large window condition. Participants are ordered according to percentage of return movements, in ascending order.

shorter view segments also show more return movements? To find out we compared the durations of the view segments on trials with return movements to those on trials without return movements, both between and within participants. In order to compare view segments with a similar probability of the item being the target, we compared the view segment containing the target before the overshoot and return movement on the trials with return movements, to the last view segment before the one containing the target on the trials without return movements. Linear regression analyses of mean duration of the view segments as a function of the percentage of return movements showed that participants with a higher percentage of return movements have shorter view segments on the trials in which they make return movements (bright grey bars in Fig. 8; slope: -2.187 ms/%, $p < 0.005$) as well as on the trials in which they do not make return movements (dark grey bars in Fig. 8; slope: -1.782 ms/%, $p < 0.05$). The view segments on the trials with return movements were also shorter than the view segments on the trials without return movements ($F(1,10) = 31.408$, $p < 0.001$). Thus return movements are associated with shorter view segments, both between and within participants.

4. Discussion

4.1. Movement planning and visual information processing

We conducted this visuo-manual search experiment to find out whether only eye movements are planned before visual information is fully processed, or whether arm movements are too.

The durations of the view segments in our experiment were much longer than the fixation durations in the experiment by Hooge and Erkelens (1996). In our experiment the mean duration of the view segments was 1170 ms for the small window condition, 668 ms for the medium window condition and 519 ms for the large window condition, while in the experiment by Hooge and Erkelens the fixations had durations (averaged over participants) ranging between 150 and 450 ms. So, in our experiment the viewing times were more than twice as long as the fixation durations in the experiment by Hooge and Erkelens. Apparently the effect of the window size puts such a severe constraint on visual processing that the gap size is no longer a limiting factor. It also makes it very unlikely that performance was limited by the planning and execution of the required eye movements in our study. The difference between the times is too large to be explained by a visuo-motor delay (Brenner & Smeets, 1997) that might be a little bit longer for the hand than for the eye, and the extra delay in the visual feedback.

Despite the very long viewing times in our experiment, participants regularly passed the target and made return movements. They moved on to the next item and then returned to the target on 37% of the trials with the large window and on 13% of the trials with the medium-sized window. In their study, Hooge and Erkelens found that participants performing a visual search task moved on to the next item after perceiving the target and made a return saccade back to the target on 5–55% of the trials. In our experiment the overshoots often did not reach the next item. The hand moves more slowly than the eyes, so that it will not have moved all the way to the next item by the time the participants realise that they have passed the target and make a correction.

The fact that return movements were found in our visuo-manual search task indicates that the visual information has not been fully processed by the last moment at which the programmed hand movement to the next item could still be cancelled. This is in contrast with the finding of Overvliet et al. (2007) that when using hand movements to search for a target among tactile items, participants never move their hand to the next item before they have fully processed the present tactile information. The main difference between our experiment and the experiment by Overvliet et al. is the modality of the information to be processed: visual items compared to tactile items. But the fact that Overvliet et al. did not find overshoots and return movements, whereas we did, is unlikely to be explained by tactile information being processed much faster than visual information, because Overvliet et al. found that the average time in contact with an item was about 550 ms, which is longer than the mean duration of the view segments in our large window condition (519 ms).

Why the viewing times in our experiment were so much longer than the fixation durations in the study by Hooge and Erkelens is not clear, because planning hand movements need not take so much longer than planning eye movements. One possible reason is that the visual stimulus is masked by the moving window.

More return movements were made when the viewing times were shorter, both between and within participants. Some participants take less time to view the items than others, thereby taking a higher risk of passing the target. This risk-taking is presumably not a deliberate choice. In a study of adjustment of fixation duration in visual search, Hooge and Erkelens (1998) found that participants could not prevent making return saccades.

4.2. Final conclusion

The participants in our experiment passed the target and returned to it in a substantial percentage of trials. From the fact that participants made return movements, we conclude that the following hand movement is planned before visual information processing is completed and that the visual information has not been fully processed by the last moment at which the hand movement to the next item can still be cancelled.

References

Ballard, D. H., Hayhoe, M. M., Li, F., & Whitehead, S. D. (1992). Hand-eye coordination during sequential tasks. *Philosophical Transcriptions of the Royal Society London, 337*, 331–339.

Becker, W., & Jürgens, R. (1979). An analysis of the saccadic system by means of double step stimuli. *Vision Research, 19*, 967–983.

Bekkering, H., Adam, J. J., Kingma, H., Huson, A., & Whiting, H. T. A. (1994). Reaction-time latencies of eye and hand movements in single-task and dual-task conditions. *Experimental Brain Research, 97*, 471–476.

Brenner, E., & Smeets, J. B. J. (1997). Fast responses of the human hand to changes in target position. *Journal of Motor Behavior, 29*(4), 297–310.

Carpenter, R. H. S. (1988). *Movements of the eyes* (2nd ed.). London: Pion Limited.

Eriksen, C. W., & Eriksen, B. A. (1971). Visual perceptual processing rates and backward and forward masking. *Journal of Experimental Psychology, 89*, 306–313.

Hooge, I. Th. C., & Erkelens, C. J. (1996). Control of fixation duration in a simple search task. *Perception and Psychophysics, 58*(7), 969–976.

Hooge, I. Th. C., & Erkelens, C. J. (1998). Adjustment of fixation duration in visual search. *Vision Research, 38*(9), 1295–1302.

Joiner, W. M., & Shelhamer, M. (2006). Pursuit and saccade tracking exhibit a similar dependence on movement preparation time. *Experimental Brain Research, 173*(4), 572–586.

Land, M. F., & Hayhoe, M. (2001). In what ways do eye movements contribute to everyday activities? *Vision Research, 41*, 3559–3565.

Mocharnuk, J. B. (1978). Visual target acquisition and ocular scanning performance. *Human Factors, 20*, 611–631.

Moffitt, K. (1980). Evaluation of the fixation duration in visual search. *Perception and Psychophysics, 27*, 370–372.

Neggers, S. F. W., & Bekkering, H. (1999). Integration of visual and somatosensory target information in goal-directed eye and arm movements. *Experimental Brain Research, 125*, 97–107.

Overvliet, K. E., Smeets, J. B. J., & Brenner, E. (2007). Haptic search with finger movements: Using more fingers does not reduce search times. *Experimental Brain Research*. doi:10.1007/s00221-007-0998-9.

Prablanc, C., Echailler, J. F., Komilis, E., & Jeannerod, M. (1979). Optimal response of eye and hand motor systems in pointing at a visual target. I. Spatio-temporal characteristics of eye and hand movements and their relationships when varying the amount of visual information. *Biological Cybernetics, 35*, 113–124.

Sailer, U., Eggert, T., Ditterich, J., & Straube, A. (2000). Spatial and temporal aspects of eye-hand coordination across different tasks. *Experimental Brain Research, 134*, 163–173.

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