

The influence of vertically and horizontally aligned visual distractors on aurally guided saccadic eye movements

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Abstract Eye movements towards a new target can be guided or disrupted by input from multiple modalities. The degree of oculomotor competition evoked by a distractor depends on both distractor and target properties, such as distractor salience or certainty regarding the target location. The ability to localize the target is particularly important when studying saccades made towards auditory targets, since determination of elevation and azimuth of a sound are based on different processes, and these processes may be affected independently by a distractor. We investigated the effects of a visual distractor on saccadic eye movements made to an auditory target in a two-dimensional plane. Results showed that the competition evoked by a vertical visual distractor was stronger compared with a horizontal visual distractor. The eye movements that were not captured by the vertical visual distractor were still influenced by it: a deviation of endpoints was seen in the direction of the visual distractor. Furthermore, the interference evoked by a high-contrast visual distractor was stronger compared with low-contrast visual stimuli, which was reflected by a faster initiation of an eye movement towards the high-contrast visual distractor and a stronger shift of endpoints in the direction of the

high-contrast visual distractor. Together, these findings show that the influence of a visual distractor on aurally guided eye movements depends strongly on its location relative to the target, and to a lesser extent, on stimulus contrast.

Keywords Saccades · Eye movements · Multisensory interaction · Auditory localization · Visual distractor

Introduction

Saccadic eye movements are made to direct the fovea onto a new target in the environment. Visual, auditory and somatosensory information around us influences the generation of saccades and can guide or disrupt goal-directed eye movements (e.g. Amlôt et al. 2003; Corneil and Munoz 1996). Although much is known about the spatial and temporal dynamics of the oculomotor competition induced by visual (e.g. Hunt et al. 2004; Theeuwes et al. 1999) and auditory elements (e.g. Frens and Van Opstal 1995), less is known about the interaction between auditory and visual information in the programming of eye movements. The aim of the present study was to investigate the effects of a visual distractor on saccadic eye movements made to an auditory target in a two-dimensional plane.

The influence of a distractor on oculomotor behaviour is generally explained in terms of the population coding theory (Tipper et al. 1997). This theory, which was originally developed to explain mechanisms of pointing movements, assumes that neurons in a motor map will code an individual vector that encodes the movement to the corresponding location. The theory has also been applied to eye movements, which are assumed to be initiated in the direction of the average of the vectors present in the oculomotor

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system (Van der Stigchel 2010). According to this theory, when a target and a distractor are presented, both stimuli will be represented in the brain as vectors in a motor map and together induce a response. The strength of each vector influences the final response, and in most cases, one of the elicited vectors will be relatively stronger compared with the other vector (Van der Stigchel et al. 2011). Top-down influences, such as instructions to look at the target or ignore the distractor, and bottom-up input, like stimulus salience, influence the eventual response. Averaging of vectors is seen in the *global effect*, whereby the saccadic endpoint is positioned at an intermediate location between two elements (Coren and Hoenig 1972; Findlay 1982; Van der Stigchel and Nijboer 2011). Stimulus properties such as brightness and size influence the global effect, whereby high-contrast visual stimuli receive priority and therefore induce a global effect which is shifted towards the high-contrast visual stimulus (Proulx and Egeth 2008). The sudden appearance of a new stimulus can even ‘capture’ the eye completely. In that case, the saccade lands at the location of the distractor, even when this object appears distant from the target. This oculomotor capture is thought to be stimulus driven and occurs without voluntary control of the observer (Godijn and Theeuwes 2002; Theeuwes et al. 1998, 1999).

Although it is possible to use an auditory stimulus as a target for eye movements (Corneil and Munoz 1996; Corneil et al. 2002; Frens and Van Opstal 1995; Stevenson et al. 2012), previous studies on supramodal oculomotor competition in a two-dimensional plane have used visual elements as the predetermined goal of eye movements (Doyle and Walker 2002; Van der Stoep et al. 2013). The results of these studies might not generalize to the situation in which an auditory target is used, since distinct processes underlie stimulus localization. Localizing auditory targets positioned in the horizontal plane (i.e. azimuth) relies on the difference in arrival times and the intensity of the stimulus between the two ears [interaural time (ITD) and level differences (ILD)]. Since human ears are vertically aligned, the ITD and ILD of auditory stimuli are the same for sounds along the vertical plane (i.e. elevation) and only provide information on the horizontal positions of the sound source. Determining the elevation of sounds relies on different mechanisms such as reflections in the pinnae (Middlebrooks and Green 1991). Additionally, the composition of the auditory spectrum is an important factor and should consist of multiple frequencies in order to correctly determine the amount of elevation (Frens et al. 1995). Elevation judgment of an auditory source heavily depends on the amount of frequencies in a sound (Good and Gilkey 1995) or visual cues (Corneil et al. 2002; Zwiers et al. 2001) and therefore seems less accurate compared with determining azimuth.

In previous studies, auditory targets were used to investigate the influence of a visual distractor in a horizontal plane (Battaglia et al. 2003; Bertelson and Aschersleben 1998; Hairston et al. 2003). In a study of Bolognini et al. (2007), participants had to name the location of auditory targets in a horizontal plane. Visual stimuli above or at threshold were presented together with the sound, and the spatial disparity was systematically varied. A localization error in the direction of the visual stimulus above threshold was observed. This perceptual bias is called the ventriloquist effect and shows that a visual stimulus can influence perception of an auditory stimulus. Interaction of auditory and visual stimuli was also observed in a study of Corneil and Munoz (1996), who investigated influences of competing auditory and visual stimuli on eye movements in the horizontal plane. More erroneous saccades were made when a visual target was combined with an auditory distractor, compared with an auditory target combined with a visual distractor. The authors argued that this difference was due to the smaller amount of central processing time required for visually guided eye movements, which resulted in less time to complete target selection, leading to more incorrect saccades towards the auditory distractor (Corneil and Munoz 1996). In their study, the locations of the stimuli were only varied in the horizontal direction. Given the differences in localizing processes, aurally guided eye movements in a vertical plane could be influenced differently by visual distractors.

In the current study, we aimed to investigate the oculomotor competition evoked by a visual distractor on eye movements towards an auditory target that varied in location in two dimensions in one depth plane. To this end, participants performed a task in which they had to execute an eye movement towards an auditory target. In the majority of trials, a visual distractor was presented simultaneously, either horizontally or vertically opposite to the target. Competition between the auditory target and visual distractor can result in capture, in which the endpoint lies at the distractor location, or in a global effect, in which the eye movement lands in between audiovisual stimuli. Because the endpoint of an eye movement reflects the outcome of the averaging of multiple signals, the current study allows for a comparison of the strengths of the contributions of the auditory and the visual input to the saccade generation in different spatial compositions. Determining elevation of a sound relies on different processes compared with determining azimuth and leads to greater uncertainty regarding localization of a sound in the vertical plane (Corneil et al. 2002; Good and Gilkey 1995; Zwiers et al. 2001). Furthermore, the time to compute the elevation component of the sound is estimated to be ± 30 ms longer compared with the time to compute

the azimuth component (Colonius et al. 2009). As the certainty and processing time regarding the target location determine the amount of influence of other possible cues during multisensory processing (Bolognini et al. 2007; Heron et al. 2004), this could lead to a greater influence of the vertically opposite visual distractor compared with the horizontally opposite visual distractor, resulting in more capture and a greater shift of endpoints towards the vertically opposite distractor. Furthermore, as spatial judgments are predominantly based on visual information (Battaglia et al. 2003), it might be that the influence of a visual distractor in the oculomotor system is much stronger compared with an auditory target. Based on this hypothesis, we also varied the contrast of the visual stimulus to explore the strength of the competition evoked by a visual distractor in the different compositions.

Materials and methods

Participants

Ten participants (mean age = 24.02, SD = 2.24 years; 5 male) were tested in this experiment for either money or course credits and had normal or corrected-to-normal visual acuity. None of the participants reported problems with hearing. The experiment was performed in accordance with the Declaration of Helsinki. All participants gave written informed consent.

Apparatus

Eye movements were recorded by an Eyelink1000 system (SR research Ltd., Canada), an infrared video-based eye tracker that has a 1000 Hz temporal resolution and a spatial resolution of 0.01°. The participants' head was stabilized using a chin rest. The distance between the screen and chin rest was 80 cm. Participants were tested having both eyes open, and the left eye was monitored. The participants were seated in a sound-attenuated, dimly lit room.

The visual stimuli were generated by an Acer X1261P projector (60 Hz) on a white screen; the size of the projection was 56 × 43 cm. At 0.25 cm behind the screen, four piezoelectric loudspeakers (0.4 W, 8 Ω) were mounted on wooden stands fixed to the table surface. The experimental computer and the speakers were linked by a Fast Track Ultra 8R USB audio interface (M-Audio, Irwindale, California, United States). The speakers were located diagonally from a central fixation point at two positions in each visual hemifield, both at 13.08° in horizontal direction and 13.08° up or down from a central fixation point (Fig. 1). The same locations for auditory and visual stimuli were used.

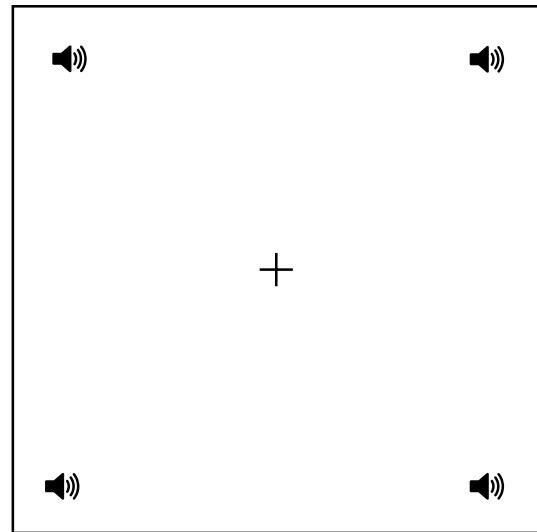


Fig. 1 Positions of the four locations of both auditory and visual stimuli

Stimuli, procedure and design

Training

In order to allow participants to practise with distinguishing sounds from different locations, they received a short training task. The locations of the loudspeakers were clearly pointed out, and the participants were told that all locations would be used during the experiment. Five sounds with intensities ranging from 53 to 72 dB were presented at the four different locations. The participants could pick the sound that they thought was most easy to localize. Next, this sound was presented two times from each loudspeaker, and the location was mentioned beforehand. Finally, the sound was played from each location one time per session where after the participants had to name the location. This procedure was repeated until the participants correctly named the location of three out of four sounds within one session, which was the case within three sessions for all participants.

Sound selection

The auditory stimuli consisted of 500-ms bursts of broadband sound. Prior to each session, a sound selection task was administered in order to obtain subjectively equal loud stimuli for each participant. Five sounds with a different intensity (53–59–64–68–72 dB) were each randomly presented 16 times at one of the four locations. Participants were asked to verbally localize the sound by choosing one of the four quadrants. The stimulus with the highest intensity that was localized correctly in all trials, and was not reported to be

uncomfortable to hear, was selected. If this was not the case for any of the sounds, the stimulus that was correctly localized in most of the trials was chosen. Participants were accurate in localizing the sound in at least 75 % of the trials.

Experiment

The fixation stimulus and high-contrast visual stimulus were black (2.16 cd/m^2 ; Weber contrast = -0.99628) on a light grey background (581 cd/m^2). Additionally, a low-contrast visual stimulus was used in half of the bimodal trials (534 cd/m^2 ; Weber contrast = -0.0809). Each trial started with the presentation of a central fixation stimulus (a black plus sign; $0.94^\circ \times 0.94^\circ$). After a variable fixation period of 550–950 ms, the fixation cross disappeared. Next, a blank screen of 100 ms was presented after which the auditory target and the visual distractor were presented for 500 ms. A visual distractor (a solid circle with a diameter of 0.94°) appeared always at a different position simultaneous with the auditory target. The trial sequence is depicted in Fig. 2. Participants were instructed to fixate at the central fixation stimulus until the onset of the auditory target and were instructed to move their eyes as quickly as possible to the target. It was stressed that they should ignore the visual distractor. Each session started with a 9-point grid calibration procedure. In addition, to assure that participants were looking at the centre of the screen at the start of each trial, the experimenter could only start the next trial by pressing the space bar when participants were gazing at the fixation cross.

There was one no distractor condition, in which the auditory stimulus was presented in isolation, and four bimodal conditions, in which the visual distractor was presented simultaneously with the sound. There were two direction conditions in which the location of the visual distractor relative to the auditory target was varied. In the vertical condition, the distractor was located at the same x-coordinate and at a different y-coordinate as the sound. In the

horizontal condition, the auditory stimulus was paired with a visual distractor that was located at the same y-coordinate but at a different x-coordinate as the sound. Furthermore, there were two contrast conditions consisting of a low- and high-contrast visual distractor.

The experiment consisted of a training session of 24 trials and an experimental session of 720 trials. Trials were randomly presented in blocks of 24 trials, consisting of 8 no distractor trials and 16 bimodal trials. In this way, each combination of the direction and contrast condition was presented four times per block (one for each of the 4 positions). After each trial in the training session, feedback was given about the accuracy of the eye movement. During the whole experiment, feedback was given about the speed of the eye movements, whereby participants were stimulated to respond as fast as possible. No feedback regarding accuracy was given anymore.

Data analysis

Saccadic accuracy was defined by calculating endpoint deviations in polar coordinates as the angular shift of the saccade endpoint relative to the angle of the vector between the saccade starting position (the fixation cross) and the target location (the sound; see Fig. 3). Saccades for all locations were recalculated to the upper right location in which positive values refer to clockwise endpoint deviations with respect to the target and negative values refer to counter-clockwise deviations (see Fig. 3). Saccade latency was defined as the interval between target onset and the initiation of a saccadic eye movement.

The initial saccade starting position had to be within 2° from the central fixation point for both the vertical and

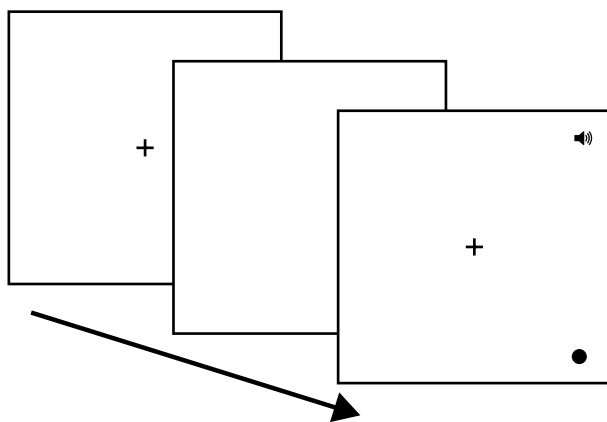


Fig. 2 Example of sequences of frames in a trial (*vertical condition*)

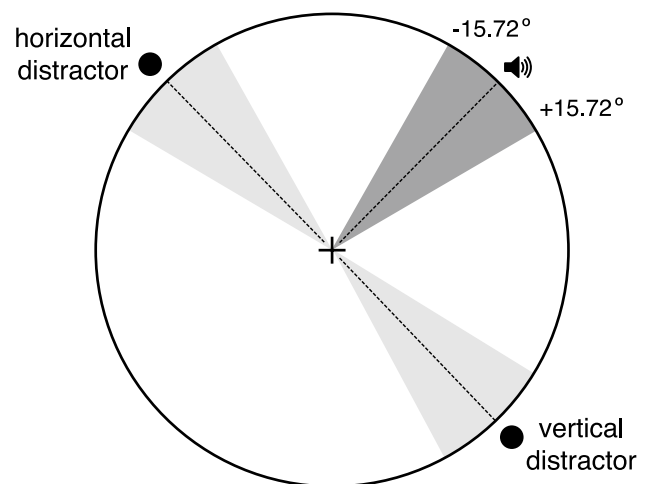


Fig. 3 Schematic representation of the saccade angle deviation measure and ranges ($\pm 15.72^\circ$) wherein saccades are called a hit (*dark grey*) or capture (*light grey*)

horizontal directions. Trials were also excluded if there was no saccade or if the first saccade was too small ($<3^\circ$). If saccade latency was shorter than 80 ms, longer than 800 ms or 2.5 standard deviations from the participant's mean latency, the trial was excluded. These exclusion criteria led to a mean loss of 4.46 % of trials.

A saccade endpoint was called a hit when its angular shift relative to the target was within the mean deviation plus one standard deviation. Values in the no distractor condition from saccade endpoints within the correct quadrant were used to calculate this range for each participant separately. Capture was defined by using the same range as for the hits, but now relative to the distractor location (see Fig. 3 for a schematic representation of these definitions).

The percentages of capture in the bimodal conditions were compared by using a repeated-measures ANOVA, using the factors direction (vertical, horizontal) and contrast (low, high) to verify whether they affected capture of eye movements differently. Furthermore, we used paired t tests to compare the percentage of capture in the direction conditions with the no distractor condition to assure that the capture was truly caused by the distractor.

In order to investigate whether a global effect was present, we analysed whether the deviation from the target of the endpoints in the distractor conditions differed from the deviation of the endpoints in the no distractor condition. For saccades landing in the quadrant of the target, we compared the mean deviation for each direction condition (vertical, horizontal,) by using a repeated-measures ANOVA, with the factor distractor (no, low-, high-contrast distractor).

Saccade latencies for hit and capture trials were compared by using a repeated-measures ANOVA, with the factors direction (vertical, horizontal,) and contrast (low,

high). Paired t tests were used to compare both direction conditions with the no distractor condition. Finally, for each direction condition, paired t tests were used to compare latencies in the hit trials versus capture trials.

Results

Sound selection

The sound intensity of 68 dB was used for six participants. Other intensities were 59 dB (1 subject), 64 dB (2 subjects) and 71 dB (1 subject).

Saccade accuracy

The distribution of saccade endpoint deviations in the no distractor and bimodal trials are shown for the vertical distractor condition in Fig. 4 and for the horizontal distractor condition in Fig. 5. The range for hits or capture was calculated for each participant, which resulted in a mean value of plus or minus 15.72° (SD = 6.98°) (see Fig. 3). In the no distractor condition, the mean deviation from the sound was 13.22° (SD = 8.56°), and 77.20 % (SD = 15.12 %) of trials were hits (see Table 1). In the vertical distractor condition, 42.49 % (SD = 25.72 %) of low-contrast trials were hits and 39.45 % (SD = 27.91 %) of high-contrast trials were hits. In the horizontal distractor condition, 74.46 % (SD = 12.68 %) of low-contrast trials were hits and 72.63 % (SD = 12.78 %) of high-contrast trials were hits.

Next, we looked at the accuracy of saccades relative to fixation, to objectify possible undershoot (saccades ending before the target location) or overshoot (saccades ending

Fig. 4 Distribution of saccade deviations for the no distractor (dark grey) and the vertical distractor condition (transparent white with black outline), the dashed lines indicate the target (0°) and distractor (90°) location

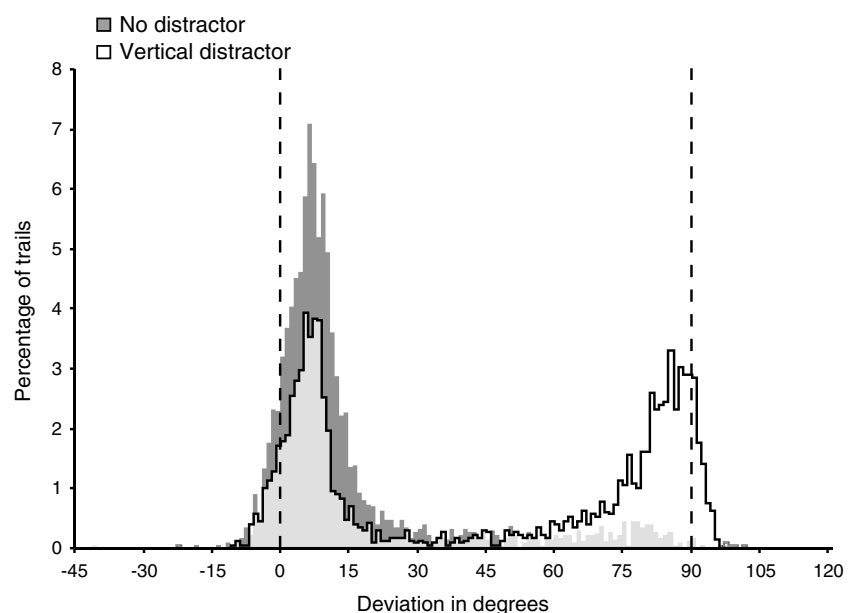


Fig. 5 Distribution of saccade deviations for the no distractor (dark grey) and the horizontal distractor condition (transparent white with black outline), the dashed lines indicate the target (0°) and distractor (−90°) location

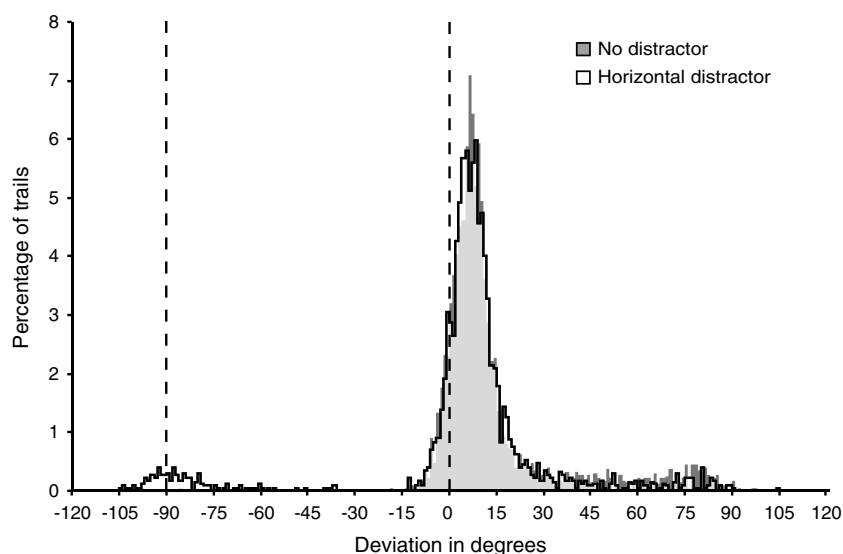


Table 1 Percentage of endpoints that were hits, capture or landed elsewhere, and the undershoot/overshoot in visual degrees relative to fixation cross and stimuli radius

	% Hits (SD)	% Capture (SD)	% Elsewhere (SD)	Undershoot/overshoot in degrees of visual angle (SD)
No distractor	77.20 (15.12)	–	22.80 (15.12)	−0.80 (2.06)
Vertical low contrast	42.49 (25.72)	38.38 (23.52)	19.13 (9.16)	−1.37 (1.76)
Vertical high contrast	39.45 (27.91)	40.16 (28.60)	20.40 (7.94)	−1.79 (1.80)
Horizontal low contrast	74.46 (12.68)	4.57 (3.78)	20.97 (11.03)	−0.97 (1.97)
Horizontal high contrast	72.63 (12.78)	5.42 (5.16)	21.94 (11.51)	−1.03 (2.01)

beyond the target location) of saccades. Targets and distractors were presented at an imaginary circle with a radius of 18.50 visual degrees (see Fig. 3). We computed the distance of endpoints to this circle, whereby a negative value indicates an undershoot and a positive value an overshoot. In the no distractor condition, saccades ended on average −0.80 visual degrees (SD = 2.06) from the circle, which was considered an accurate endpoint. In Table 1, the average distances of all conditions are displayed. A larger undershoot is seen in the distractor conditions, especially in the vertical distractor condition. This can be explained by the capture trials: saccades that are captured by a distractor are in general shorter compared with saccades that where hits (Van der Stigchel and Nijboer 2010). We did not exclude saccades based on this distance, since the percentage of capture would have been underestimated.

Capture

First of all, the percentage of capture trials in the bimodal conditions were compared using the factors direction and contrast. There was a significant main effect of direction on percentage capture trials [$F(1,9) = 18.63$, $p = .002$],

whereby in 39.27 % (SD = 8.00 %) of all trials in which a vertical distractor was present, the eyes were captured by the distractor, whereas capture occurred in only 5.00 % (SD = 1.33 %) of all trials in which a horizontal distractor was presented. No main effect on contrast, [$F(1,9) = 0.30$, $p = .597$], or interaction effect, [$F(1,9) = 0.05$, $p = .827$], was seen, which indicates that the salience of the distractor did not influence the amount of capture in any of the distractor conditions.

To verify whether eye movements were truly captured by the distractor or whether these percentages reflect normal variation in saccade endpoints, we compared the percentage of capture with the percentage of endpoints at that same location in the no distractor condition. Of all endpoints in the no distractor condition, 3.35 % (SD = 3.92 %) of eye movements landed at the vertical distractor location, which was significantly less compared with trials in which a vertical distractor was actually present (39.27 %; SD = 8.00 %; $t(9) = -5.13$, $p = .001$). Only 0.09 % (SD = 0.18 %) of trials in the no distractor condition landed at the location of the horizontal distractor, which was also significantly less compared with trials in which a horizontal distractor was actually shown (5.00 %; SD = 1.33 %; $t(9) = -3.85$,

$p = .004$). This indicates that the presence of the visual distractor was responsible for the capture of eye movements.

Endpoint deviation of non-capture saccades

The mean deviation of the eye movements that landed in the quadrant of the target was first compared between the no distractor, low- and high-contrast *vertical* distractor conditions. Note that all eye movements landing within the quadrant of the target were analysed, which allowed us to analyse whether both hits and endpoints in between the target and distractor were influenced by the experimental conditions. There was a significant main effect of distractor [$F(2,18) = 4.89, p = .020$]. Post hoc pairwise comparisons revealed a trend of endpoints shifting in the direction of the low-contrast visual distractor (mean deviation 8.79° , $SD = 5.09^\circ$; $p = .074$), and a significant shift of endpoints in the direction of the high-contrast visual distractor (mean deviation 10.68° , $SD = 7.18^\circ$; $p = .035$), compared with the no distractor condition (mean deviation 7.86° , $SD = 4.16^\circ$). The same comparison was made for the *horizontal* low- and high-contrast visual distractors, in which no shift of endpoints due to the horizontal distractor was seen [$F(2,18) = 1.83, p = .188$].

Saccade latency

Hits

Latencies in hit trials in the bimodal conditions were compared. One participant did not show any hit trials in the case where a vertical distractor was present. Therefore, data of the nine remaining participants were analysed. There was a significant main effect of the factor direction on latency [$F(1,8) = 7.75, p = .024$]. Latencies of correct eye movements in the presence of a horizontal distractor were shorter (244 ms, $SD = 22$) compared with the presence of a vertical distractor (260 ms, $SD = 27$). No main effect on contrast, [$F(1,8) = 0.55, p = .478$], was observed, indicating that the salience of the distractor did not influence saccade latency. Finally, no interaction effect between direction and contrast [$F(1,8) = 2.18, p = .178$] was observed, indicating that contrast did not influence saccade latency different in one of the two direction conditions.

To investigate whether latencies also differed from the no distractor condition, latencies from hit trials in the no distractor condition were compared with latencies of hit trials in both direction conditions. Latencies of hit trials in the no distractor condition (224 ms, $SD = 66$) were significantly lower compared with those in the horizontal distractor condition (238 ms, $SD = 67$; $t(9) = -4.10, p = .003$) and vertical distractor condition (254 ms, $SD = 78$; $t(9) = -7.05, p < .001$). This indicates that the distractor

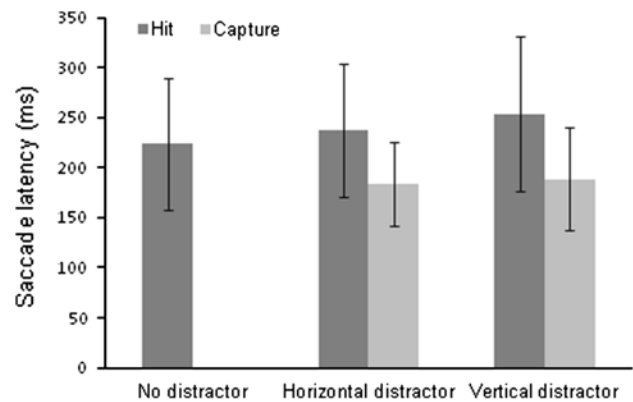


Fig. 6 Saccade latencies depicted for the different conditions; error bars depict standard deviation of the mean

interfered with eye movements to the target, which caused longer latencies (also known as the remote distractor effect, Walker et al. 1997). In Fig. 6, the latencies are depicted for the no distractor, horizontal and vertical distractor conditions.

Capture

Latencies of eye movements that were captured were compared between the bimodal conditions. There was a significant main effect of contrast [$F(1,7) = 13.76, p = .008$], in which latencies of eye movements which were captured by the high-contrast visual distractor were shorter (168 ms, $SD = 12$) compared with the low-contrast visual distractor (187 ms, $SD = 16$). No main effect of direction, [$F(1,7) = 3.82, p = .092$], or interaction effect, [$F(1,7) = 0.23, p = .648$], was observed.

Hits versus capture

Finally, the difference in latencies between hit trials and capture trials was investigated for each direction condition (see Fig. 6). In case of a vertical distractor, latencies in hit trials (254 ms, $SD = 78$) were significantly higher compared with latencies in capture trials (188 ms, $SD = 52$; $t(9) = 7.06, p < .001$). Two of the participants did not show capture in case of a horizontal distractor at all, and their latencies were not taken into account when comparing the hits and captures within the horizontal condition. When a horizontal distractor was shown, latencies in hit trials (217 ms, $SD = 54$) were also significantly higher compared with latencies in capture trials (184 ms, $SD = 42$; $t(7) = 3.20, p = .015$).

The latencies of the captured eye movements were shorter compared with the latencies of the correct eye movements, which means that the faster the eye movements were initiated, the more mistakes were made. This

speed–accuracy trade-off is in line with findings from previous studies (Munoz and Corneil 1995; Corneil and Munoz 1996) and has been explained by the reflexive nature of capture saccades. Capture saccades are executed on the basis of bottom-up information without involvement of slower, top-down processes (Godijn and Theeuwes 2002).

Discussion

In the current study, we showed that a vertical visual distractor evokes stronger oculomotor competition (39 % capture) in making eye movements towards an auditory target compared with a horizontal visual distractor (5 % capture). Eye movements that were not captured by a vertical distractor were still influenced by it: a deviation of endpoints was seen in the direction of the visual stimulus. The difference in evoked competition between horizontal and vertical distractors was also reflected in the difference in saccade latencies: in case of trials in which the eye movement landed correctly at the target (hit trials), latency was longer when a vertical distractor was present compared with hit trials in which a horizontal distractor was shown. Our results therefore implicate that the strength of the vector evoked by the visual distractor depended largely on its location relative to the auditory target: the visual distractor evoked a strong vector when positioned in the vertical direction from the target, resulting in a large amount of capture and a global effect, whereas the strength of the vector was relatively weak when the distractor was positioned in a horizontal direction from the target. Note that the high percentage of capture in the vertical distractor condition was not due to guessing of the participant about the exact location of the target: almost all eye movements in the trials without a distractor landed correctly at the target location, showing that the oculomotor capture was genuinely induced by the presence of the distractor.

The difference in competition evoked by the vertical and the horizontal distractor might be explained by the underlying mechanisms to determine sound locations. The azimuth of a sound is derived from binaural cues while the elevation of a sound is based on the reflections in the pinnae (Middlebrooks and Green 1991). It takes more time for the elevation component to be computed, and this difference is estimated at ± 30 ms (Colonus et al. 2009). In our experiment, the visual and auditory stimuli were presented at the same moment. It is possible that the saccade was already induced before the elevation component of the sound was computed, leading to the perception of the visual and auditory stimuli at the same vertical position. This could have caused more capture by the vertical distractor compared with the horizontal distractor. Furthermore, higher latencies

in hit trials were seen when a vertical distractor was present compared with a horizontal distractor. The extra time that was needed to compute the elevation component could account for the higher level of interference of the vertical distractor.

Additionally, vertical localization of a sound source is generally less accurate compared with horizontal localization of a sound source (Corneil et al. 2002). The uncertainty about the location of the target versus distractor might therefore have been much stronger when a horizontal distractor was presented compared with when a vertical distractor was presented. As it is known that the global effect is smaller when greater certainty exists about the target location (Vander Stigchel and Nijboer 2011), the stronger competition evoked by a vertical distractor might be evoked by the great uncertainty in target localization in this condition. These findings are also in line with the observation that the uncertainty about the target stimulus influences the weight of a distractor during multisensory processing (Bolognini et al. 2007; Heron et al. 2004).

Besides location, the contrast of the visual distractor influenced the strength of its vector, which was reflected in the global effect. Eye movements that landed in the quadrant in which the target was located landed more in the direction of the vertical distractor compared with trials in which no distractor was present. However, a high-contrast visual stimulus caused a greater shift in endpoints compared with a low-contrast visual stimulus. Additionally, a difference in latency was observed between the low- and high-contrast distractors in case of a capture trial. The high-contrast distractor caused eye movements to be initiated faster compared with the low-contrast distractor. The contrast of the distractor did not significantly influence the amount of capture of the eye movements: even the low-contrast visual stimulus caused capture in over one-third of trials. The finding that no difference in capture rate was observed between the low- and high-contrast distractors could therefore be due to a ceiling effect. Because of the strong interference evoked by a visual distractor when presented together with an auditory target, insufficient inhibition on a given trial results in the capture of the eyes by the distractor, irrespective of its contrast.

Previous studies have mainly studied the effects of auditory distractors on eye movements towards visual targets (Bolognini et al. 2005; Colonius and Arndt 2001). For instance, it was shown that an auditory stimulus at a distant location can influence the trajectory of saccadic eye movements towards a visual target (Doyle and Walker 2002; Frens et al. 1995). In line with these findings, the current experiment showed that a distant *visual* distractor can affect the endpoint of eye movements towards an *auditory* target. Information from the different modalities is thus combined in the brain, and both modalities affect

the eventual response. A structure that is important in the programming of saccades and has also been associated with multimodal processing is the superior colliculus (SC) (Sparks 1986; Sparks and Hartwich-Young 1989). A majority of the neurons in deeper layers of the SC receive and process information from more than one sensory area, for example from the occipital cortex, the auditory cortex and/or the somatosensory areas (Edwards et al. 1979; Sparks and Hartwich-Young 1989). It is proposed that both auditory and visual information are represented in a multimodal motor map in the SC (Doyle and Walker 2002; Frens et al. 1995). This makes it possible for a supramodal vector to emerge within the SC and affect the eye movement trajectory.

In the current experiment, a visual distractor evoked strong competition in the oculomotor system when presented in the same visual hemifield as the auditory target. In contrast, the visual stimulus in the opposite visual hemifield hardly affected eye movements that were made towards the target. A difference between vertical and horizontal eye movements is reported in previous studies: trajectories of saccades directed to a visual vertical target deviated more away from a visual distractor compared with saccades directed to a visual horizontal target (Laidlaw and Kingstone 2010; Van der Stigchel and Theeuwes 2008). This behavioural finding was explained by pointing to the structure of the SC, which is divided into two separate retinotopic neuronal maps (Hall and Moschovakis 2003). When the horizontal target and distractor are represented in the same collicular motor map, only local inhibition can take place, because inhibition of the complete neural map would result in inhibition of the target as well. In case the target and distractor are not located within the same hemifield, the complete motor map representing the distractor can be inhibited, leading to stronger inhibition of the distractor (Van der Stigchel and Theeuwes 2008). Given the large effect in the current study between vertical and horizontal distractors, it is unlikely that such a mechanism would fully explain the observed difference between the amount of capture induced by vertical and horizontal distractors, but it is possible that the simple positioning within the same or different motor map contributes to the strength of the oculomotor inhibition evoked by a distractor.

To conclude, when making eye movements to a sound, visual stimuli located vertically opposite to the sound evoke stronger competition compared with visual stimuli located horizontally opposite to the sound, resulting in capture of eye movements and a global effect. Furthermore, high-contrast visual stimuli have greater influence compared with low-contrast visual stimuli, which is reflected by a faster response and a stronger shift of endpoints in the direction of the distractor. Our results further support the

combination of supramodal target and distractor information in the oculomotor system.

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Conflict of interest The authors declare that they have no conflict of interest.

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