Selection of the hand path in obstacle avoidance

Daniel Baldauf

Center for Mind/Brain Sciences, University Trento, Italy

In two EEG experiments we studied the role of visual attention during the preparation of manual movements around an obstacle. Participants performed rapid hand movements to a goal position avoiding a central obstacle either to the right or to the left, depending on the pitch of the acoustical go-signal. We used a dot probe paradigm in order to analyze the deployment of visual attention in the field during the motor preparation. Briefly after the go-signal but still before the hand movement actually started a visual transient was flashed either on the planned pathway of the hand to the left or right of the obstacle (congruent trials) or on the opposite, movement-irrelevant side (incongruent trials). The P1/N1-components that were induced by the onset of the dot probe were enhanced in congruent trials where the visual transient was presented on the planned path of the hand. The results indicate that during movement preparation attention is allocated to the planned trajectory the hand is going to take around the obstacle.

Introduction

When we act in complex environments the avoidance of obstacles becomes a key problem of movement programming. Whether we reach out for the salt that is on a crowded table right behind the full glass of water or whether we grasp the spoon that lies close to the cup of hot tea, our goal-directed movements are often at risk to interfere with other objects that we need to avoid. Although adults avoid obstacles with apparent ease, such coordinate movements represent a difficult task, which necessitates several years of training - as can be observed in the development of infants and children.

The elaborateness of implementing such a task can also be estimated from robotics engineering. Here, two prominent accounts have been put forward. The first one implements the avoidance of an obstacle by potential fields, which either attract or repulse the robotic effector. The optimal path along which the effector will go around an obstacle and reach the final goal is a dynamic combination of the repulsion from the obstacle and the attraction to the goal location. A second and biologically more plausible account uses intermediate goals, so-called milestones to compute a route around an obstacle. Here, the space of interest is likened to a roadmap, which is first sub-classified into 'forbidden regions', i.e., the obstacle(s), and 'free space' (everywhere else except the obstacles). If the obstacle is in between the starting point and the goal, potential intermediate goals are constructed in the free space and again the algorithm tests for possible collisions. Here multiple alternative routes via various potential intermediate goals have to be compared and one is finally selected as the actual path. One critical problem here is

that the best path remains under-determined. In order to find the optimal path complex functions have to be integrated along all possible trajectories and the outcomes have to be compared – a computational effort that takes time.

This problem is also well known in human movement science, mostly referred to as the problem of *motor equivalence* (Lashley, 1930; Bernstein, 1967): Every goal position can be reached through an infinite number of ways (path under-determination). So far it remained unknown how the brain chooses one movement path - say for the hand reaching around an obstacle - from all the possible alternatives. This is not only true for a given effector. Furthermore, a certain motor output can also be achieved by different effectors, as has been prominently illustrated in the case of cursive handwritings (e.g., Lashley, 1942; Wright, 1993; Meulenbroek et al., 1996). And from those studies of handwriting a possible solution to the problem of motor equivalence has been formulated by proposing a simple model that could simulate motor equivalent writing movements (Meulenbroek, 1996; see also van der Wel et al., 2007). According to this model, hand writing is described as a sequence of movements, so-called writing strokes, each of which has not only a goal but also goes through an invariant *via point*. The authors argue on the basis of their simulations that actors have access to abstract spatiotemporal forms, such as the repetitive succession of via points and goals in handwriting, and that these spatiotemporal forms allow to produce similar motor output with different effectors as well as to scale the output to different absolute sizes (see also, e.g., Keele, Cohen & Ivry, 1990). Van der Wel and collaborators (van der Wel et al., 2007) demonstrated now that also in manual obstacle

avoidance such abstract spatiotemporal forms play an important role: Their data suggest that trajectories around an obstacle can be primed by previous movements (see also, Jax & Rosenbaum, 2007) and that these priming effects generalize over the workspace and scale with the height of the obstacle. Here, the spatiotemporal form of the movements around an obstacle could be either the whole shape of the trajectory or individual via points, e.g., the points of maximal excursion or the points of maximal velocity - as in the case of writing-movements. The combination of a via point and a final goal is therefore a biologically plausible way to choose a path around an obstacle – similar to what robots do.

What does this mean for the visual perception? As many studies have demonstrated we do not process all incoming visual information to the same extent but filter out irrelevant parts in order to select and process in depth only those parts of the visual scene that are relevant to our behavioral goals. In terms of movement preparation it has been shown for example that attention pre-selects the goal location for an intended eye-movement (Kowler et al., 1995; Deubel & Schneider, 1996). Further, visual attention also serves the preparation of goal-directed manual reaches (Baldauf et al., 2006).

Moreover, the selection of goals for upcoming movements is not restricted to single locations. It has been shown that multiple movement goals were selected in parallel before movement onset if several movements were planned in rapid succession (Baldauf et al., 2006; Baldauf & Deubel, 2008 a,b; Baldauf et al., 2008a). In such cases, the attentional spotlight splits into multiple, spatially distinct foci (Baldauf & Deubel 2008 a, b), forming an 'attentional landscape' (Baldauf & Deubel, 2010; Baldauf, 2011). Some rare experiments also studied the distribution of visual attention in situations in which obstacles had to be avoided by manual reaches to a target (Deubel & Schneider, 2003). Here again, covert attention was not only restricted to the goal of the reach but the obstacle was co-selected, as well, before the movement was initialized. Johansson and coworkers tracked open gaze while participants manually transported objects around an obstacle. They found that participants often fixated the obstacle before and during movement execution (Johansson et al., 2000). One conclusion that can be drawn from all these instances is that the visual resources are flexibly adjusted to the actual behavioral needs, i.e. to whatever is relevant for the preparation of an upcoming movement.

Do actors also attend to the path they choose around an obstacle? Given that invariant spatiotemporal forms, like via points, play a role for the programming of the reach around an obstacle, such relevant positions may be visually selected in advance before piloting through them. A via point could function as an intermediate goal and may be co-selected by visual attention, similarly as immediate and subsequent goals are selected in reach sequences (Baldauf & Deubel, 2010; 2006; Baldauf et al., 2008a,b).

In the present event-related potential (ERP) study we tested with a dot-probe paradigm the hypothesis that visual attention selects critical locations along the upcoming path around an obstacle. Particularly, we were interested in the distribution of visual attention in the field during the preparation of obstacle avoidance reaches. We analyzed the amplitude of the neural response (ERP) elicited by the onset of a task-irrelevant probe stimulus to infer how much processing resources were allocated to a certain location. The visual ERP has previously been shown to be particularly sensitive to the direction of spatial attention: probe stimuli that were flashed at attended locations elicit bigger sensory-evoked P1/N1 components than identical stimuli at unattended locations (Luck & Hillyard, 1995; Luck et al., 1994; Mangun, Hillyard & Luck, 1993; Baldauf & Deubel, 2009).

Experiment 1: Congruent vs. incongruent side

Methods:

Participants:

Eleven students, aged between 24 and 32 (5 female) participated in both experiments. They had normal or corrected-to-normal vision and were right-handed. They were paid for their participation and gave their informed consent in advance of the experiments.

Experimental setup:

Figure 1 provides a sketch of the experimental setup. The participants sat in a dark room. The visual stimuli were presented on a 21-inch monitor (100Hz frame frequency, 1024x768 pixels resolution). The active screen size was 40x30 cm at a viewing distance of 58cm. The hand movements were performed on a slightly inclined working plane in front of the participant. A half-translucent mirror was placed in front of the subject such that the visual stimuli appeared to be projected onto the working plane. This mirror allowed hand movements without visual feedback about the position of the hand. All visual stimuli had a luminance of 23 cd/m2 and were presented on a grey background with a mean luminance of 2.2 cd/m2. A central loud speaker in the back of the participant delivered the auditory cues.

A Fastrak electromagnetic position and orientation measuring system (Polhemus Inc, 1993) continuously recorded the movements of the right hand. The system consists of a sender unit and a small receiver mounted on the tips of both index fingers. The sender unit was placed at a distance of 60 cm from the participant. The device had

a spatial accuracy of 0.03 inches and a frequency bandwidth

Figure 1: A: Experimental setup. The visual stimuli appeared on a video display and were projected via a half-translucent mirror onto the working plane. The visual stimuli were congruent with the 3D obstacle mounted in the working space below the mirror. A Polhemus Fastrak electromagnetic tracking system recorded the hand movements. **B:** Sequence of stimuli in Experiment 1. The display continuously showed the margin of the obstacle around the central fixation point. In the upper part of the display a cross represented the stationary reach target. Further a box was provided, in which the participant had to position her/his right index finger at the very beginning of each trial. After a random interval of an acoustical go-signal was provided which had either a high or low pitch. As soon as the participants heard this go-signal they had to reach for the target avoiding the obstacle. Shortly after onset of the go-signal but before movement initialization a visual transient was flashed for 70ms equidistantly either to the right or left of the obstacle. In each trial the flashed dot appeared either on a position that the hand was planned to move through or at the opposite, movement irrelevant side of the obstacle. After the goal was reached a LED mounted on the index fingers tip provided feedback about the reaching accuracy.

of 120Hz. The signal delay was approximately 4 ms. In order to provide visual feedback about the hand position during an initial positioning period and after execution of the reach a small LED (5mm in diameter) was attached to the sensor and controlled by the computer. Eye fixation was controlled by EOG. An adjustable chin rest helped reducing movement artifacts.

Stimuli and Procedure:

Figure 2 shows the succession of stimuli in a typical trial of Experiment 1. The screen continuously displayed a starting box, in which the right index finger had to be placed at the very beginning of each trial, the margin of a static obstacle in the centre, and a target cross in the upper half of the screen. Further a small fixation cross was provided in the centre of the obstacle. Spatially congruent with the visual outline of the obstacle a real wooden cylinder was positioned in the pointing plane. The cylinder had a diameter of 8 cm and was 2 cm in height. The relatively small height of the obstacle allowed the participants to comfortably reach around on both sides.

The margin of the obstacle was congruent with the surrounding of a wooden cylinder placed on the working plane. When the trial started participants used the illuminated LEDs on the tips of their index fingers to position their hands in the starting box. Then the LEDs were extinguished and after a random interval of 600 to 900 ms an acoustical go-signal was presented, which had a frequency of either 500 or 200 Hz. The participants had to reach with their right hand around the obstacle to the target as soon as they heard the go-signal. If the go-signal was a low-frequency beep the participants had to avoid the central obstacle via the right-hand side, if the go-signal was a high frequency beep they reached the target on a route along the left-hand side. The participants were asked to reach for the target as fast and as accurately as possible. Strong emphasis was placed on never to touch the obstacle. After the execution of the required movement participants received visual feedback about their pointing accuracy at the reach target.

In order to measure the deployment of visual attention during movement preparation a task irrelevant dot probe was flashed 150 ms after the acoustic go-signal – well before the instructed reach actually started. The dot probe was a circular disk with a diameter of 1.2 deg and appeared for 80 ms either to the right or to the left of the obstacle with an eccentricity of 8 deg. The lateral distance from the object was adjusted in pretests such as to ensure that the dot probe was flashed close to the trajectories the participants would actually take. Therefore each subject performed a pretest block of 100 trials without EEG recording. This pretest revealed that most participants chose a very similar path around the obstacle and pass the cylinder in a distance of on average 6.4 deg.
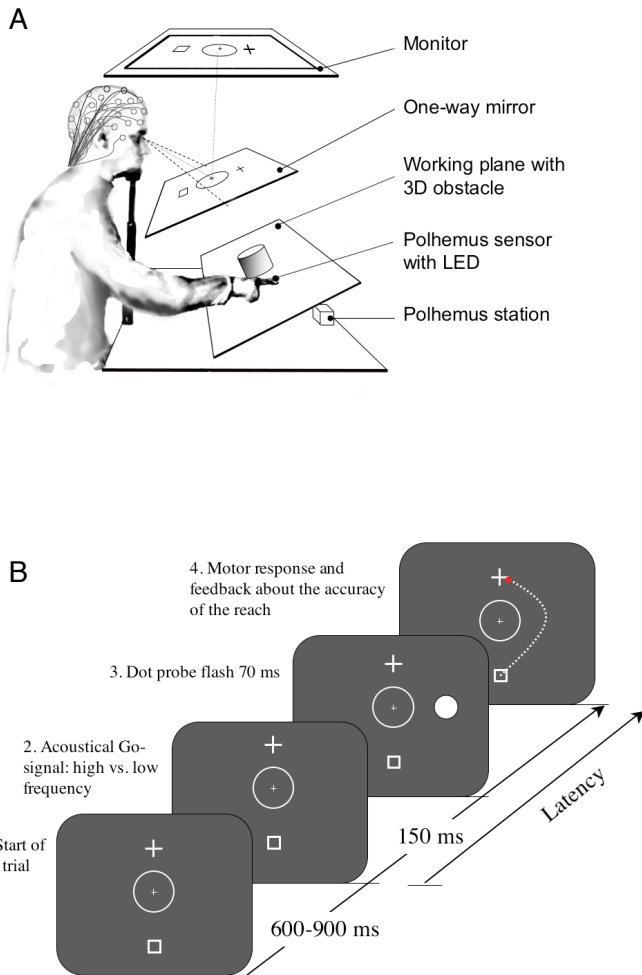
Design

The participants performed four experimental blocks, each consisting of 100 trials. The go-signal instructed to reach either with the left or with the right hand around the obstacle along the respective pathway. The critical factor that was varied in this experiment was the position of the dot probe relative to the instructed movement path: (1) in congruent trials the dot probe appeared on the side where the hand was planned to move along; (2) in incongruent trials however the dot probe was flashed on the opposite, movement-irrelevant side. In total this led to 4 different conditions (2 pathways x 2 dot probe positions). The conditions were randomized in each trial and each condition was repeated 25 times in each block.

Recordings

We used a BrainAmp system (Brain Products, Munich, Germany) to continuously record from 64Ag/AgCl electrodes mounted in an elastic cap (EasyCap, FMS). The electrodes were placed according to the international 10-10 system and referenced to Cz. The horizontal electro-oculogram was bipolarly recorded from the outer canthi of both eyes. The vertical electro-oculogram was recorded from electrodes above and below the left eye. All electrode impedances were kept as equal as possible and below 5kOhm. The signals were amplified and filtered online by a 0.1-100 Hz bandpass filter. The digitalization rate was 500 Hz. The recorded signals were then 40 Hz low-pass filtered offline.

The continuous EEG data was epoched into analysis windows of 600 ms duration, starting 100 ms before and ending 500 ms after the presentation of the go-signal. Trials with eye blinks (a voltage at Fpz exceeding +/- 80µV), saccadic eye movements (a voltage at hEOG or vEOG exceeding +/- 80µV) or with muscle artifacts (a voltage at any site exceeding +/- 100µV) were excluded from further analysis. After rejecting trials exceeding the above mentions threshold there was still some residual activity in the EOG channels caused by small eye movements counterbalancing the deviations in head position when the reach was initialized.

The analysis of the EEG data revealed that the elicited ERPs were hardly lateralized. Therefore, we computed separated ERP averages only for the two relative positions of the dot probe with respect to the instructed pathway (congruent versus incongruent), irrespectively of the hemifield, in which the dot probe had been flashed. All epochs were time-locked to the onset of the dot probe. The averages were computed relative to the 100 ms baseline before the onset of the go-signal.

We calculated separate repeated-measures ANOVAs to analyze the mean amplitudes of the P1 and N1 components that were elicited by the dot probes appearing at the two relative positions. The two factors of these ANOVAs were Probe position ('congruent' vs. 'incongruent') and

Electrode site with the levels 'O1', 'O2', 'P3', 'P4', 'C3', and 'C4'. Statistical analyses were done with the 'R' statistical package (Ihaka & Gentleman, 1996).

Results:

Rejection of trials:

5.4% of all trials were rejected because eye movement occurred or because of other artifacts in the EEG (e.g. muscle activity). Since we wanted to ensure that the dot probe was presented during the movement preparation period we also excluded 3% of the trials with latencies shorter than 220 (150 ms SOA + 70 ms presentation time of the dot probe) and 7% of trials with movement onset latencies longer than 600 ms.

Movement performance:
Figure 2a gives an example of some typical trajectories around the obstacle for one participant. The mean spatial error between the final landing position and the centre of the target was 1.08 deg. Interestingly, the trajectories are rather similar across trials. The participants efficiently chose an optimal path for the reaching hand, which stayed remarkably constant.

Figure 2b and c show the latencies of movement along the left versus right path. When reaching along the left path the hand started on average 392 ms (SE= 32 ms) after onset of the go-signal. For reaches along the right path mean latency was on average 402 ms (SE=35 ms). The reaching movements took on average 251 ms. Since the task-irrelevant visual transient served as a measure of the distribution of visual attention, it should not affect the motor task such that, for example, its appearance on the planned trajectory hampers or delays the movement that is about to be programmed. Therefore, we analyzed whether the movement latencies depended on the relative *Probe position*. A one-way ANOVA did not show a significant main effect of the probe position on the latency of the movement onset (p>0.4). The movement latencies did not differ significantly between trials were the probe was on the planned trajectory and trials in which the dot-probe was presented on the opposite, movement-irrelevant side.

After initialization the hand moved in a homogenously bended trajectory around the obstacle. The point of maximum excursion was reached after about xxx ms on about the same level with the obstacle, but with an horizontal offset of about 9.4 deg (9.6 deg on the left and 9.1 deg on the right-hand side). At this point the trajectories also had the minimum curvature. This "viapoint" was spatially congruent with the point of maximum velocity
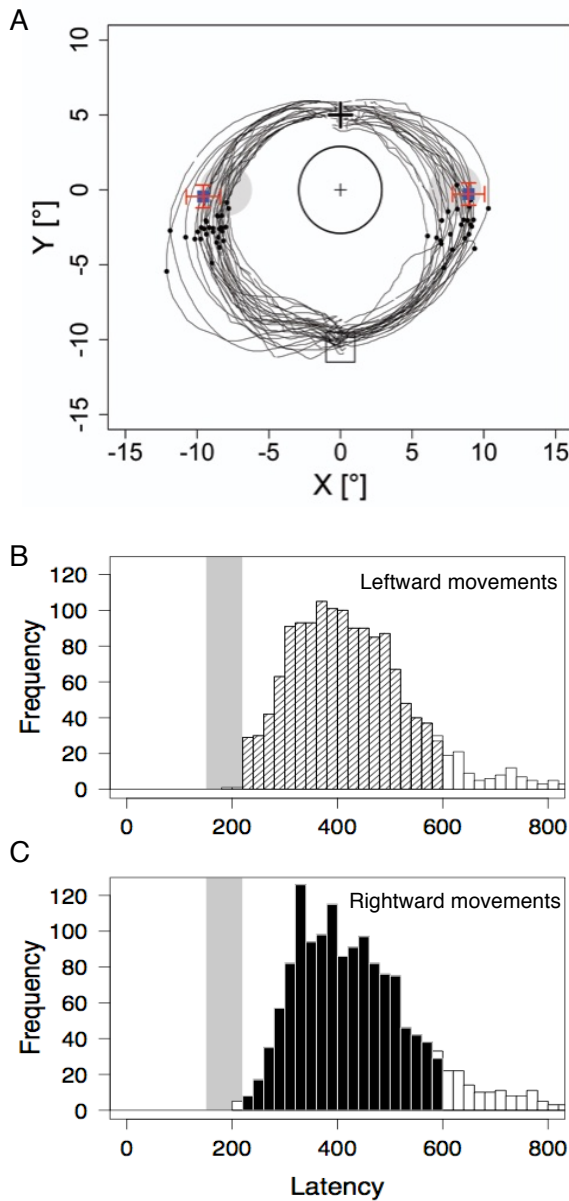
A

B

C

Figure 2. A: Some typical trajectories with the left or right hand around the obstacle in Experiment 1. The shaded areas underlying the trajectories on the right and left hand side depict the locations where the dot probes were flashed during movement preparation in Experiment 1. The little black dots on each of the trajectories show the 'via points' of the movements, at which the lateral excursion was maximal. Superimposed is the mean via point across all nine participants (blue). The Error bars in red indicate one standard deviation. The Histograms show the movement onset latencies of reaches along the right-hand (**B**) and left-hand side (**C**). Open bars represent those trials that had been excluded from further analysis because the movement started too early or too late (see METHODS). The area shaded in grey represents the period in time at which the visual transient is flashed.

Event-related potentials:

We analyzed the event related potentials that were evoked by the flashing of the visual transient before movement onset, in order to test whether parts of the path the going is panned to take are visually selected in advance. The ERPs were collapsed across the hemifields, in which they appeared, but contrasted on basis of their relative position in relation to the planned movement route (DP at congruent vs. incongruent side). Figure 4a depicts the grand-averaged ERPs that were elicited at Oz by dot probes that either lied on the planned path of the hand (congruent, solid line) or on the opposite, movement-irrelevant side of the obstacle (incongruent, dashed line). Both ERPs were characterized by prominent P1- and N1-components in response to the flashed probe. The P1 peaked 126 ms after onset of the dot probe, the N1 reached its maximum about 182 ms after the probe. Both the amplitude of the P1- and of the N1-component were enhanced if the visual transient was flashed on the planned route for the hand compared to the movement-irrelevant side. Figure 4b provides an overview over the elicited components at other electrode sites. The evoked components were most prominent at occipital (and parietal) sites (e.g. O1, O2, PO7, PO8, PO3, PO4, P3, P4) and decrease in amplitude at more anterior sites (e.g. C3, C4). Also the observed modulation of the P1- and N1-components, i.e. the difference in amplitudes of components that were evoked by transients on the congruent versus incongruent side, was more pronounced at posterior sites.
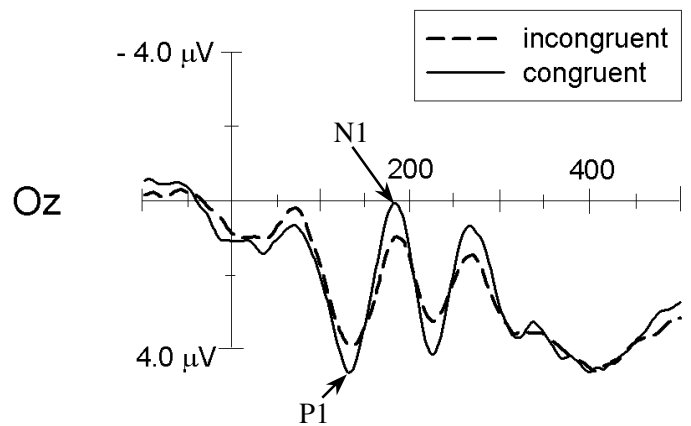

Figure 3. Grand-averaged ERPs that were evoked by task irrelevant dot probes at an occipital site (Oz). A time interval starting 100ms before and ending 500ms after the onset of the dot probes is shown. The dot probe was flashed peripherally either at the same side as the hand was instructed to reach along (congruent, solid line) or at the opposite side (incongruent, dashed line).
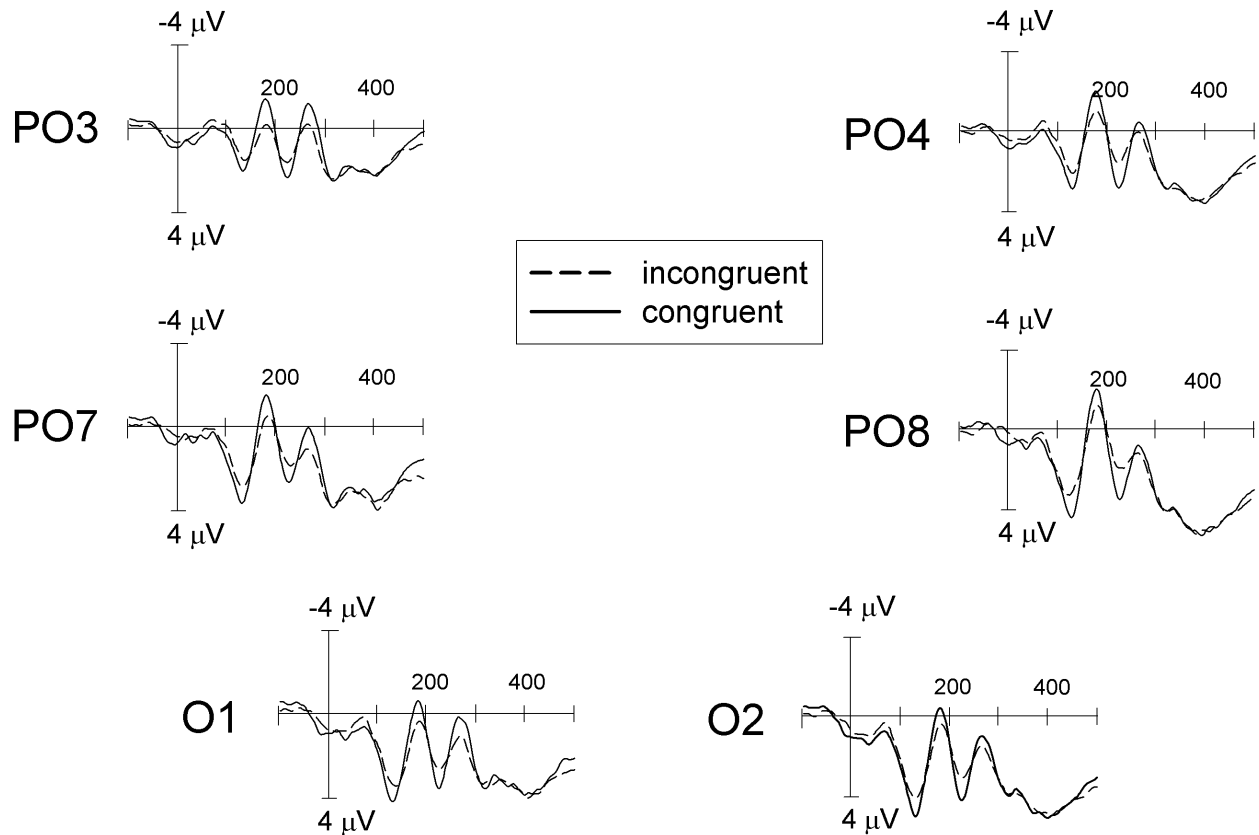
Figure 3. Grand-averaged ERPs that were elicited at occipital and parietal-occipital sites. A time interval starting 100ms before and ending 500ms after the onset of the dot probes is shown. The dot probe was flashed peripherally either at the same side as the hand was instructed to travel along (congruent trials, solid line) or at the opposite side (incongruent trials, dashed line).

Statistical analyses further affirmed the modulation of the ERP components. For quantitative comparison of the components we extracted the mean voltages of the P1 and N1 amplitudes in a time window of 30 ms around the respective peak. For the P1 component this interval ranged from 111 to 141 ms (peak of the P1 at 126 +/- 15 ms) and for the N1 the interval was from 167 to 197 ms after probe onset. For both data sets we computed a two-way ANOVA. Here, the first factor was the relative 'Probe position' with the levels "congruent" and "incongruent". The second factor coded the electrode site and had the levels "O1", "O2", "PO/", "PO8", "PO3", "PO4", "P3", "P4". The ANOVA for the P1-component revealed a significant main effect of both factors as well as a significant interaction (ME 'probe position': $F[1, 10]=9.10$, $p< .002$ and ME 'electrode site': $F[7, 70]=8.63$, $p< .001$; Interaction 'Probe position' x 'electrode site': $F[7, 70]=2.21$, $p< .05$). The interaction of both factors is most likely due to the fact the visual components (and so their modulations) were much stronger pronounced at occipital sites and dissipated at more anterior electrodes. The main effect of the relative 'Probe position' on the amplitude of the N1-component did not reach significance ($F[1, 10]=3.34$, $p< .09$), but the main effect of electrode side did ($F[7, 70]=4.10$, $p< .001$).

Discussion:

In Experiment 1 we used a dot-probe paradigm to probe the distribution of visual attention in the scene, while participants prepared to reach around a central obstacle. The results show that during the preparation period of these movements the visual system preferentially processes visual input from the movement-relevant side of the obstacle as compared to input from the movement-irrelevant side. In this first Experiment the probe was well outside of the obstacle and therefore the results suggest that visual attention is not only directed to the goal or the obstacle itself. Also other parts of the scene that are of prior interest during the planning stage, namely the future hand path, are pre-selected in advance.

Experiment 2: The obstacle's margin

Experiment 1 showed that the side along which the participant is going to reach around an obstacle is preferentially processed during movement preparation. In advance of the movement initialization attentional resources are allocated to the movement-congruent side resulting in enhanced visual ERP-components in response to movement-irrelevant probe stimuli. We interpret this as an attentional bias towards the route along which the hand is planned to travel. But what is about the obstacle itself? Previous studies reported the attentional selection of hindering objects during movement preparation. For example, Johansson and colleagues (2001) found that an obstacle was fixated in about 80% of trials when actors manoeuvered around it. Further, Deubel and Schneider (2004) showed by a secondary discrimination task that attention is covertly deployed to a central obstacle immediately before reach initialization. In Experiment 2 we will compare the attentional facilitation on the future hand path with the attentional facilitation on the obstacle itself. The quantitative comparison may provide a clue about whether the observed bias towards the reach path, as observed in Experiment 1, is just a side effect of the selection of relevant object parts, such as the object's margin. Alternatively, the future hand path and the obstacle may be attended to a similar extent.

Methods:

Participants, experimental stimuli and procedure:

Six students, aged between 25 and 29 (3 female) participated in Experiment 2. They had normal or corrected-to-normal vision and were right-handed. Figure X illustrates the modified experimental stimuli in Experiment 2. The participants now had to fixate their eyes on the cross that marked the goal location on the upper end of the display. In the lower visual field was a starting box, from which the right index finger had to start the reach. Further, the margin of a central obstacle was continuously displayed, which was congruent with the same three-dimensional obstacle as in Experiment 1 underneath the mirror-setup.

When the acoustical go-signal was presented (500 or 200 Hz) the participants had to reach with their right hand along the respective route around the obstacle to the target. Again speeded responses were required and it was emphasized never to touch the obstacle. After the movement was finished visual feedback about the pointing accuracy was given.

Again, a task-irrelevant dot probe was flashed for 80 ms (SOA 150 ms) during movement preparation, either (1) at the side where the hand was instructed to reach along, or (2) on the margin of the obstacle that faced to the instructed reach path, or (3) at the other incongruent side. The metrics of the dot probe were kept the same. All dot probes were equidistantly presented with an eccentricity of 8 deg. The lateral distance from the object was adjusted to coincide with the reach paths as revealed in the pretests of Experiment 1.
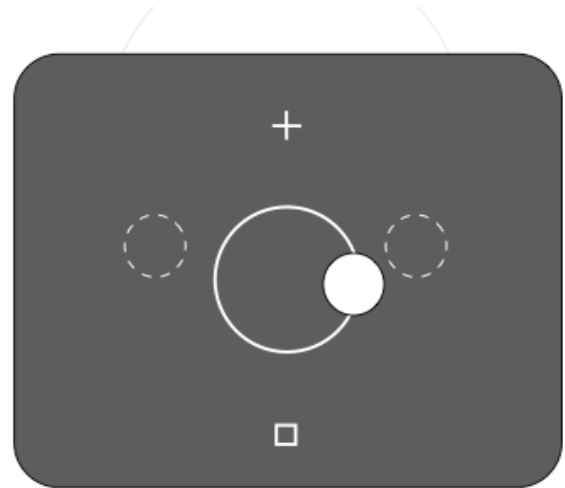

Figure 4. Possible probe positions in Experiment 2. In Experiment 2 participants fixated the goal-location throughout the trial. The task-irrelevant dot probes were flashed equidistantly to the fixation cross either on the planned movement path (congruent) or on the opposite side (incongruent) or on the relevant margin of the obstacle.
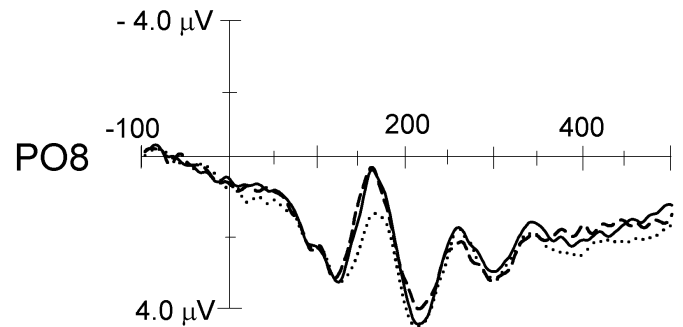

Figure 5. Grand-averaged ERPs that were evoked by dot probes at a parieto-occipital site (PO8). A time interval starting 100ms before and ending 500ms after the onset of the dot probe is shown. The dot probe was flashed peripherally either at the same side as the hand was instructed to travel along (congruent, solid line) or at the opposite side (incongruent, dotted line) or at the relevant margin of the obstacle (margin, dashed line).
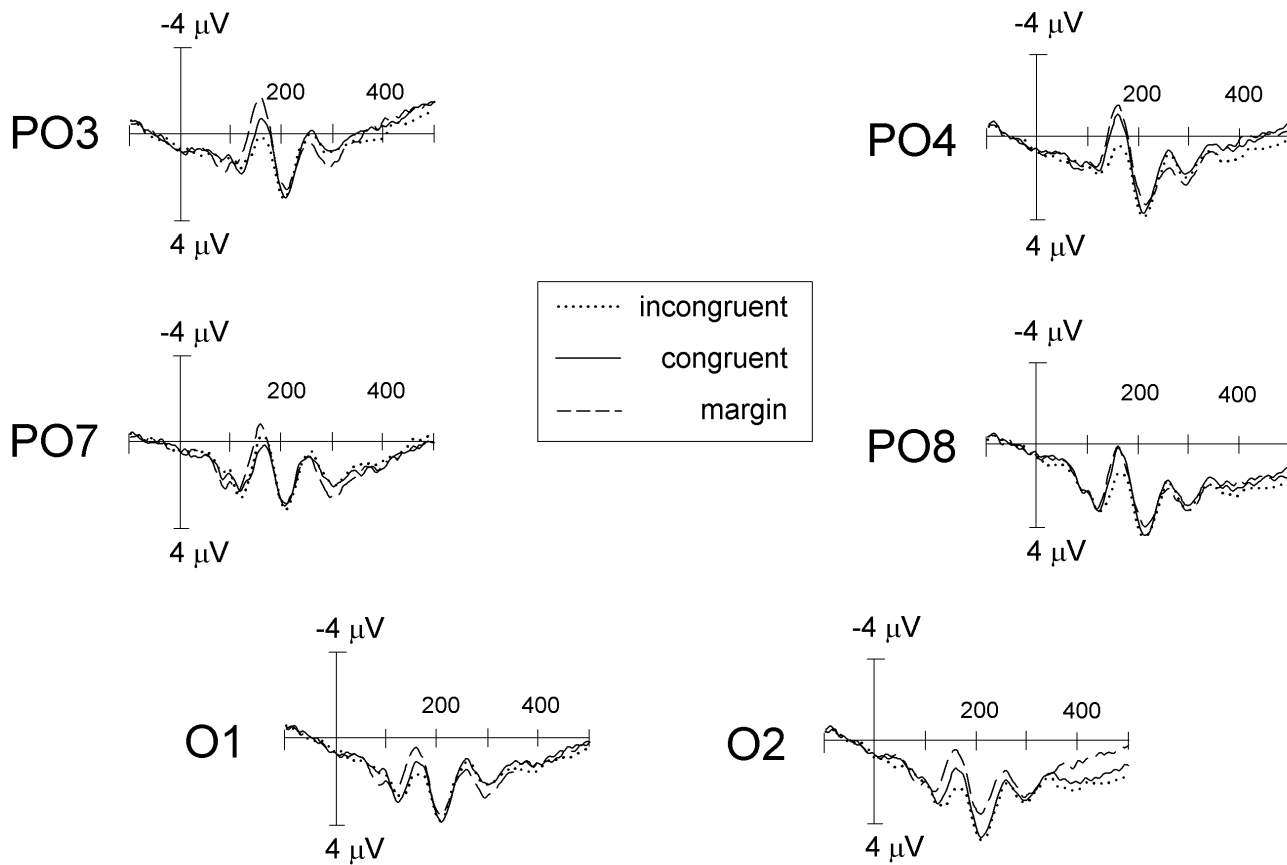
Figure 6. Grand-averaged ERPs that were elicited at occipital and parietal-occipital sites in Experiment 2. A time interval starting 100ms before and ending 500ms after the onset of the dot probes is shown. The dot probe was flashed peripherally either at the same side as the hand was instructed to travel along (congruent trials, solid line) or at the opposite side (incongruent trials, dashed line).

General Diskussion

Experiment 1 showed that the side along which the participant is going to be reach around an obstacle is preferentially processed during movement preparation. In advance of the movement initialization attentional resources are allocated to the movement-congruent side resulting in enhanced visual ERP-components in response to movement-irrelevant probe stimuli. Two alternative mechanisms could have caused this result. One could imagine, for example, that the obstacle primarily received full attention and that the programming of the avoidance path just biased the attention towards the movement-relevant side. More concretely, actors could specifically attend to the relevant-sided margin of the obstacle. Therefore, the facilitated processing on the planned path would have been the result of visual attention asymmetrically radiating from the obstacle. From previous studies it is already known that obstacles are attended to some extent during movement preparation (Deubel & Schneider, 2003). From this perspective we would assume that attentional effects are strongest at the obstacle and gradually decrease the with increasing distance from the obstacle. Such an attentional gradient could be biased towards the movement-relevant side of the configuration.

An alternative could be that the brain actively programmed an intermediate goal aside of the obstacle in order to start approaching the final reach goal only after reaching through this via point. This second account follows the ideas of Meulenbroek et al. (1996), namely that movement preparation relies on spatiotemporal forms and that goals and via points, such as the point of maximal excursion, could in combination provide such a form. Here, one would predict that the path around an obstacle is pre-selected as a separate landmark, spatially distinct from the

obstacle itself. In Experiment 2 we refined the attentional probing paradigm and flashed the dot probe occasionally on the relevant margin of the obstacle. The ERPs in response to probes on the margin of the obstacle were then compared to those ERPs that were evoked by dot probes on the future hand path or on the opposite, task-irrelevant side (as baseline).

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