



Action goal selection and motor planning can be dissociated by tool use

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ABSTRACT

The preparation of eye or hand movements enhances visual perception at the upcoming movement end position. The spatial location of this influence of action on perception could be determined either by goal selection or by motor planning. We employed a tool use task to dissociate these two alternatives. The instructed goal location was a visual target to which participants pointed with the tip of a triangular hand-held tool. The motor endpoint was defined by the final fingertip position necessary to bring the tool tip onto the goal. We tested perceptual performance at both locations (tool tip endpoint, motor endpoint) with a visual discrimination task. Discrimination performance was enhanced in parallel at both spatial locations, but not at nearby and intermediate locations, suggesting that both action goal selection and motor planning contribute to visual perception. In addition, our results challenge the widely held view that tools extend the body schema and suggest instead that tool use enhances perception at those precise locations which are most relevant during tool action: the body part used to manipulate the tool, and the active tool tip.

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1. Introduction

Perception is enhanced at the goal of body movements during their preparation, relative to other locations. Such movement-related perceptual enhancement has been shown for saccadic eye movements (e.g., Deubel & Schneider, 1996; Doré-Mazars, Pouget, & Beauvillain, 2004), manual reaching (Deubel, Schneider, & Paprotta, 1998) and grasping movements (Deubel & Schneider, 2004; Schiegg, Deubel, & Schneider, 2003). Despite the fact that such an effect of action on perception has been observed in many studies, it remains unclear what cognitive processes underlie this effect. The intentional selection of a visual object as the goal of the next movement could lead to privileged perceptual processing at the spatial location of the goal; alternatively, planning a movement with specific motor coordinates could lead to enhanced perception at the end position of the planned movement. Usually, our actions are appropriate to the objects they aim for, and thus the position of the movement goal and that reached by the body movement coincide spatially. However, to examine

which action process – goal selection or motor planning – underlies perceptual enhancement, these two positions must be dissociated experimentally.

The aim of the current study was to systematically dissociate the goal from the motor endpoint of a manual pointing movement. We did this by asking participants to point to visual targets with the tip of different hand-held tools (see illustrations in Fig. 1a). The position that must be reached by the finger while moving the tool (i.e., the motor endpoint) was different from the movement goal (the visual target the participants were to point to with the tool tip), the difference between the two depending on the shape of the tool. Participants prepared to place the tip of the tool on the visual target cued by a central arrow. During movement preparation, visual discrimination stimuli were presented at different positions, corresponding to the movement goal (tool endpoint), the motor endpoint (fingertip endpoint) or one of several other locations.

If perceptual enhancement at aimed-for locations depends on goal selection processes, then perception should be enhanced only when the discrimination target appears at the tool endpoint location (i.e., at the cued movement target location). If, on the contrary, motor planning

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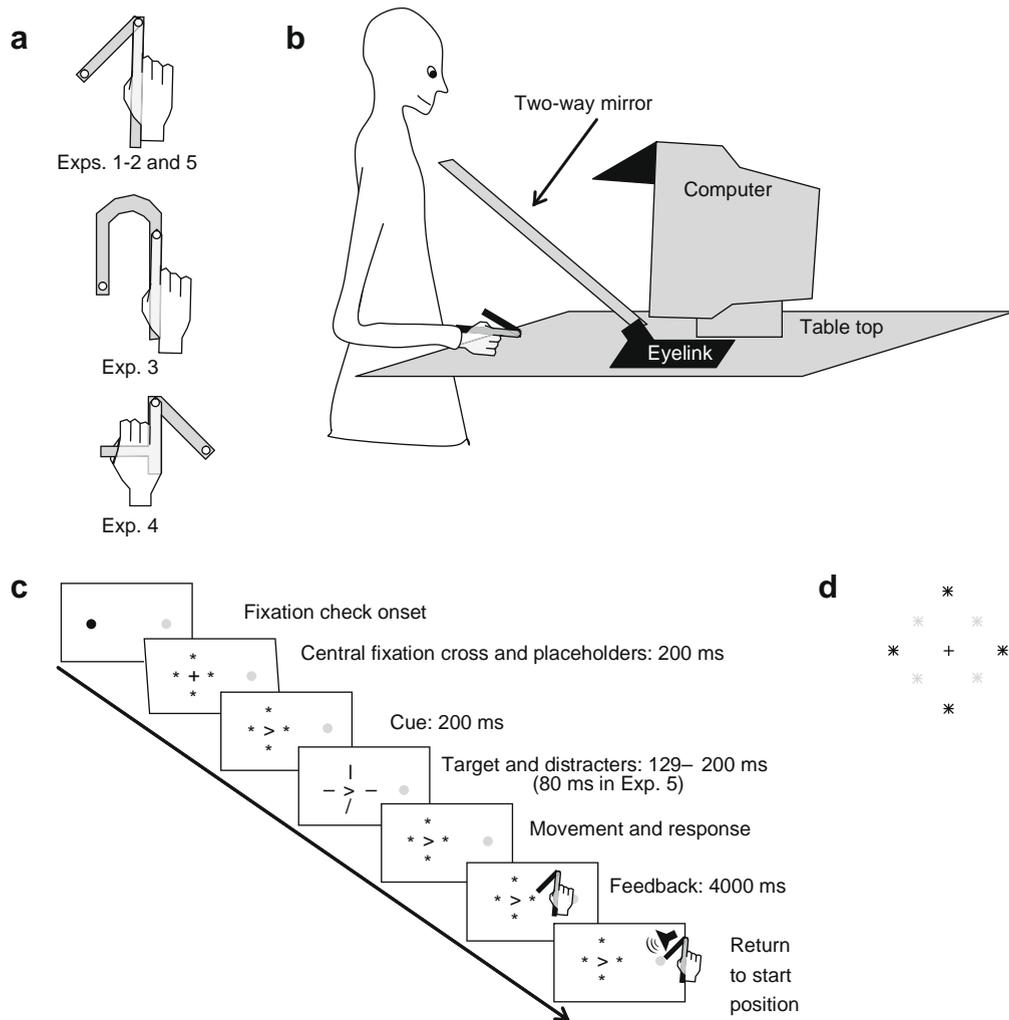


Fig. 1. (a) Diagram of the hand-held tools used in Experiments 1, 2 and 5 (top), 3 (middle) and 4 (bottom). The angle between the fingertip and the tool tip (on which a recording device was placed, here represented by the small white circles) was always 45° . (b) Experimental set-up. Participants moved their hand below a two-way mirror onto which stimuli were projected such that they appeared to be located on the table top (near the hand). The computer screen was hidden from view. (c) *Procedure*: Participants fixated the black dot and pressed on a button when they were ready. The dot was replaced by a cross and star-shaped placeholders for 200 ms, after which the cross was replaced by an arrow cue indicating the movement goal. Before movement onset, the placeholders were replaced by three distracters (– and |) and one discrimination target (DT) (/ or \) for 129–200 ms. After their movement, participants responded about the tilt of the DT (left \ or right /). The response triggered the lights below the two-way mirror, allowing participants to check the accuracy of their movement for 4 s. A tone then indicated that they were to return the tool to the start position. One second later, the lights turned off and the black dot appeared to initiate the next trial. (d) Probed locations for Experiments 1, 3–5 (black) and 2 (black and grey).

processes lead to perceptual enhancement, then performance should be better when the discrimination target appeared at the location of the finger motor endpoint. A third possibility is that both goal selection and motor planning influence perception. In that case, we would expect perceptual performance to be better at both the cued location and at the motor endpoint relative to other locations.

We ran five experiments. Experiments 1–4 tested discrimination performance at different locations on and around the finger and tool with tools of various shapes. Our aim was to determine at which locations perceptual enhancement occurred. Experiment 5 examined performance in a task which required two targets to be compared. The goal was to determine whether perceptual

enhancement occurred in parallel or serially between cued and motor endpoint locations.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Nine right-handed participants (aged 20–42 years, mean 30 years; five women) with normal visual acuity and no known neurological disorders took part in exchange for payment or course credit. One of the authors (T.C.) took part. All others were naïve regarding the object of the experiment. All gave their informed consent prior to start-

ing the experiment, which was carried out according to the ethical standards of the Declaration of Helsinki (2008).

2.1.2. Stimuli and instruments

Visual stimuli were 1° by 1° black asterisks (*), line segments (| – \ /), and arrowheads (∨ ^ <) on a white background. The stimuli were presented on an Iiyama MS103DT 21" screen (vertical refresh rate 170 Hz) and were viewed on a two-way mirror placed at a 45° angle with respect to the bottom of the screen, such that they appeared to lie on the table top (Fig. 1b), about 65 cm away from the participants. View of the real screen was occluded. Participants held the tool in their right hand. The movement start position was a red dot on the right of the screen; participants held the tool such that the tool tip was at this start point. They pointed by placing the tool tip onto the cued location. Eye fixation was monitored with an Eyelink 1000 Remote (SR Research, Osgoode, Ontario, Canada), at 500 Hz sampling rate. Hand movement was recorded at a sampling rate of 50 Hz with a Zebri CMS30P motion measurement system (Zebri Medical GmbH, Isny, Germany) using two motion sensors, one placed under the fingertip, and one under the tool tip (Fig. 1a).

2.1.3. Procedure

The structure and sequence of events are illustrated in Fig. 1c. Each trial began when participants fixated a central black dot and pressed a button held in the left hand (i.e., the hand that was not holding the tool). The dot was replaced by a cross and asterisk-shaped placeholders for 200 ms, after which the cross was replaced by an arrow cue indicating which of the four placeholders participants were to point to (upper, lower, left or right relative to central fixation). Each placeholder was 5° from the fixation cross. Before movement onset, the placeholders were replaced by three distracters (– and |) and one discrimination target (DT) (/ or \) for 129–200 ms (determined individually for each participant, see below). No visual onsets occurred; distracters and target required offsets of certain segments making up the asterisk. After their movement, participants responded about the tilt of the DT by pressing a button on the button box. Left responses (\) were given with the index finger and right responses (/) with the thumb. If at any point before or during target presentation the eye position was outside a box $\pm 1.5^\circ$ around the central fixation cross, the trial was aborted and later rerun. The response triggered four 20-watt lights below the two-way mirror which made the mirror see-through, allowing participants to see their hand and check the accuracy of their movement. After 4 s, a tone indicated that they were to return the tool to the start position. One second later, the lights turned off and the central black dot appeared, initiating the next trial. When the lights were on, eye fixation was not required. Participants were instructed to perform the movement as soon as they saw the cue, and to make note of the discrimination target to report later.

The duration of DT and distracter presentation was determined individually. Participants performed a pre-test of 192 trials during which no pointing movement was re-

quired but central fixation was checked. The central cue indicated the location of the DT. The DT and distracters were presented for 50, 100, 150 or 200 ms. Based on a regression analysis of discrimination performance, we determined for each individual participant the presentation time at which discrimination was 85% correct and used this value in the main experiment. Participants also performed a short movement pre-test to practice positioning the tool tip on the four possible movement targets (10 trials per movement goal, randomly interleaved). Throughout the entire 40 trials of this practice session, the lights under the two-way mirror were left on so that participants could use visual information to guide their movement. The within-participant standard deviation was approximately 3 mm in the horizontal and vertical directions in this practice session.

One experimental session consisted of 192 trials and lasted 60–75 min. Each combination of cued location (upper, lower, left or right) and DT location (upper, lower, left or right) was equiprobable and occurred 12 times per session. In half of the cases, the DT was tilted to the right, and in the other half to the left. Both distracter types were always present, i.e., the oblique DT was never surrounded only by vertical or only by horizontal lines.

The spatial set-up of the distracters and DT was arranged such that when the cued target was the lower or the left location, the tip of the finger of the hand holding the tool moved towards another of the four possible DT locations. This enabled us to test if discrimination was enhanced at the cued target location (tip of the tool), and also at the motor endpoint location (tip of the index finger, see Fig. 1a). Because of the shape of the tool and the way in which participants held it, with their finger extending along the shaft of the tool, we assumed that the relevant motor position was the fingertip. (We further tested this assumption in Experiments 3 and 4.)

2.1.4. Data analyses

During a session, fixation was broken in $6 \pm 6\%$ of trials (mean \pm standard deviation). These were detected online and rerun. A further $3 \pm 3\%$ of the individual data was eliminated post-hoc because of errors, lack of movement or trials in which movement onset occurred before target presentation. Movement was considered erroneous when its endpoint was closer to a target other than the instructed one. Movement velocity was derived from the sampled movement position data by calculating the slope between each two neighboring data points. Movement onset was defined as the first point in time after presentation of the movement cue at which the velocity of five consecutive movement sampling points was different from zero. Movement offset was defined as first point in time after movement onset at which the velocity of five consecutive data points was equal to zero. Movement duration was calculated as movement offset minus movement onset. Note that with a sampling rate of 50 Hz (i.e., 20 ms per data point), our method of calculating movement on- and offset potentially overestimates the real timing of these events by about 100 ms.

Discrimination target locations were grouped over the cueing conditions according to their status as the cued

target (CT), the motor endpoint (ME), nearby or other locations, and percent correct discrimination was calculated for each. “Nearby” refers to DT locations whose distance from the cued target was identical to that between the cued target and motor endpoint locations (i.e., the lower location when a movement to the left was cued, and the left location when a movement to the bottom was cued), and was a subset of the “other” locations. The mean values over all participants for these locations were tested for statistical effects using two one-factorial ANOVAs for repeated measurements: (1) CT vs. ME vs. other and (2) CT vs. ME vs. nearby.

2.2. Results

Movement was accurate despite the fact that participants could not see their hand during movement: the standard deviation of the 10–20 cm long pointing movements was about 8 mm (Fig. 2a). Movement latency was the delay between cue presentation and movement onset, and was 823 ± 529 ms (mean \pm standard deviation), and mean movement duration was 963 ± 177 ms.

Preparing to point with the tool enhanced perception at the location of the cued target and at the location of the motor endpoint (Fig. 2b). The first ANOVA revealed that there was a significant main effect of DT location ($F(2, 16) = 19.7, p < .0001$). Planned comparisons revealed that discrimination was significantly better at the cued target location ($84 \pm 10\%$) relative to the motor endpoint location ($77 \pm 7\%$) and other locations ($63 \pm 8\%$) (CT vs. ME, $F(1,$

$8) = 7.2, p < .03$; CT vs. other, $F(1, 8) = 25.7, p < .001$). Targets at the motor endpoint location were significantly better discriminated than those at other locations ($F(1, 8) = 19.3, p < .003$).

This pattern of perceptual enhancement could result from a gradient of attention centered on the cued target and extending to nearby targets such as the motor endpoint location. Thus, perceptual enhancement at this location could result from its proximity to the cued target. If this were the case, then perception of DTs presented at nearby locations that did not correspond to the motor endpoint should also be enhanced. We tested this with the second ANOVA. There was a main effect of DT location ($F(2, 16) = 18.0, p < .0001$). With respect to the nearby locations ($64 \pm 9\%$), perception was significantly enhanced at both the cued target and motor endpoint locations (CT vs. nearby, $F(1, 8) = 28.6, p < .001$; ME vs. nearby, $F(1, 8) = 12.6, p < .008$) (Fig. 2b).

2.3. Discussion

Our results confirm previous reports of perceptual enhancement at the goal of a manual pointing movement during its preparation (Baldauf, Wolf, & Deubel, 2006; Deubel et al., 1998). They extend them by disentangling goal selection from motor planning and showing that both of these processes contribute to the perceptual enhancement observed at the movement goal location. The stronger enhancement observed at the cued target location compared to the motor endpoint location sug-

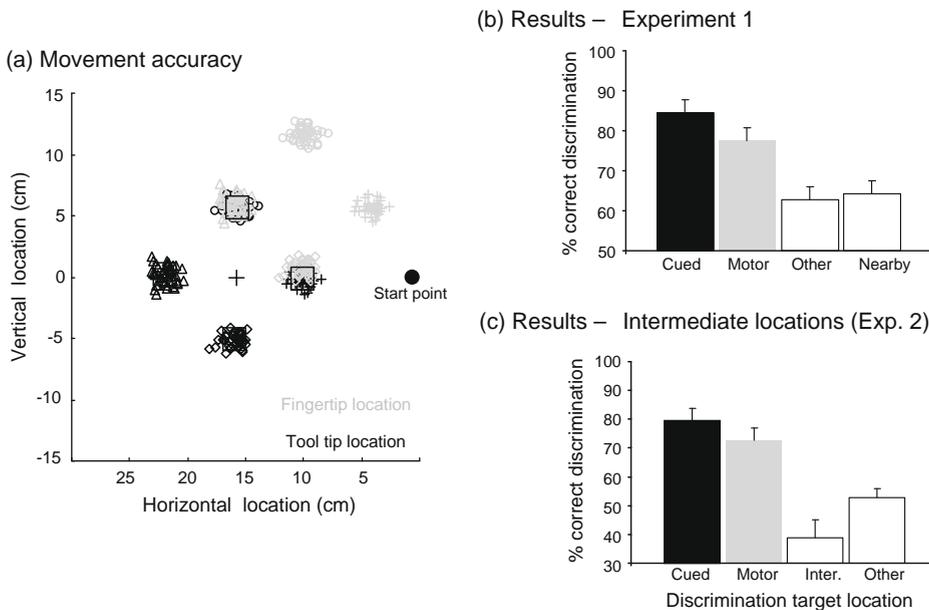


Fig. 2. (a) Motor endpoints in an individual participant (S5). The dark symbols correspond to the tool tip with which participants pointed to the visual stimuli, the grey symbols to the fingertip, placed along the shaft of the tool. The actual visual targets are symbolized by the four large squares (1.2 by 1.2 cm). Trials in which movement endpoints were closer to a target other than instructed as well as trials in which participants did not move their hand were excluded from the analyses and are not shown. (b) First experiment, percent correct discrimination as a function of the discrimination target location (cued, motor, other, nearby). Bars indicate percent correct discrimination for each location; black histograms correspond to the cued location and grey to the motor endpoint location. Error bars indicate s.e.m. (c) Second experiment, percent correct discrimination as a function of discrimination target location (cued, motor, intermediate, other).

gests that the weights of each source of information are not equal.

Perceptual enhancement at a given spatial location relative to others has been termed “selective visual attention”, the position of best perceptual performance indexing the attentional focus (Posner, 1980). Visual attention has been described as a spotlight that sweeps the visual field and highlights spatially contiguous regions of space (e.g., Broadbent, 1982). An extension of this model is the gradient model, where maximal perceptual enhancement is found at the center of the spotlight and decreases as one nears the edges (Downing & Pinker, 1985). The perceptual enhancement at the motor endpoint was less than at the cued location, and thus could reflect a gradient centered on the cued location. We examined perceptual performance at two locations at equal distance from the cued target, the motor endpoint and the nearby location. The motor endpoint was enhanced relative to the nearby location, suggesting that it was not the proximity to the cued target location that led to the enhancement of the motor endpoint.

One might speculate that the attention gradient was biased along the segment of the tool, thereby conferring a perceptual advantage to the cued target location (tool tip) and motor endpoint but not to nearby locations. Indeed, the spatial extent of the attentional spotlight can be modified according to task demands (LaBerge, 1983) and such a mechanism might serve to modify the shape of the attention gradient here. We would then expect a DT presented at a location on the segment of the tool to be better discriminated. We tested this in Experiment 2.

3. Experiment 2

3.1. Methods

Six participants (aged 20–40, mean 27; two women; one author) who also participated in Experiment 1 took part in exchange for payment. All gave their informed consent prior to starting the experiment, which was carried out according to the [Declaration of Helsinki \(2008\)](#).

Stimuli and procedures were identical to Experiment 1, except that eight placeholders indicated the locations at which the DT might occur. The four new placeholders were located midway between the original four locations. Movement was cued to the same four locations as before (Fig. 1d). To minimize the time spent standing in front of the mirror, DTs were tested only at the “intermediate” location relative to each cued location (for example, when the tool tip was to be moved to the lower target, the motor endpoint was the right location; we then tested DTs only around the lower location). Participants were instructed to expect a DT at any of the eight locations, and none reported being aware of the unequal distribution of DT locations. Each cued location – DT location combination was tested eight times per session.

DT locations were grouped into four categories: CT, ME, intermediate (i.e., between the tool tip and the fingertip), and other locations. Mean discrimination performance values (percent correct) were analyzed with a repeated measurements one-factor ANOVA.

3.2. Results

There was a main effect of DT location ($F(3, 15) = 30.1, p < .004$). Discrimination performance of DTs at the cued target location ($78 \pm 13\%$) was better than at the motor endpoint location ($70 \pm 9\%$) ($F(1, 5) = 9.6, p < .02$), the other locations ($55 \pm 5\%$) ($F(1, 5) = 30.1, p < .004$), and, critically, the intermediate locations ($42 \pm 15\%$) ($F(1, 5) = 59.7, p < .001$), which were not discriminated above chance (Student t -test: $t_{(5)} = 1.3, p > .2$) (Fig. 2c). Discrimination performance at the motor endpoint location was better than that at the intermediate and other locations ($F(1, 5) = 43.0, p < .002$; $F(1, 5) = 19.5, p < .008$). Interestingly, performance was worse at the intermediate location than at other locations, although this difference was only marginally significant ($F(1, 5) = 4.3, p < .09$).

3.3. Discussion

Perceptual performance at locations between the motor endpoint and the cued target was not enhanced, thus the hypothesis that an attentional spotlight included the entire tool was not confirmed. The distance between the tool tip and the fingertip was only 8.4 cm (equivalent to 10° of visual angle). Such fine-tuned deployment of spatial attention has previously been reported in the context of the preparation of multiple sequential hand reaches (Baldauf et al., 2006). In that study, perceptual judgments were enhanced at all movement goal locations (up to three tested), but not between them. That attention can be directed to noncontiguous locations in space has also been suggested in other studies, for example when attention is directed to perceptual groups defined by object motion (Driver & Baylis, 1989). Evidence for divided visual-attentional foci has also been obtained from electrophysiological recordings (Müller, Malinowski, Gruber, & Hillyard, 2003).

Performance at the intermediate locations was slightly worse than at other locations. This may relate to recently reported findings of a suppression of attention immediately surrounding the focus of attention (Hopf et al., 2006). The intermediate location was located between the two attentionally enhanced locations (cued target and motor endpoint), and may thus receive inhibition from both attentional foci, leading to a decrease of performance in comparison to other unattended locations.

We have so far implicitly assumed that the perceptual enhancement at the motor endpoint of the index finger is related to the planned movement of this finger. However, the tool used in Experiments 1 and 2 was shaped such that the tip of the index finger lay on the corner between the shaft and the leftward-extending segment. Such a sharp edge may constitute a salient location on the tool, for example because tool edges are potentially important for the way the tool must be handled. The attentional enhancement at the finger endpoint may result from the tool shape rather than from motor planning itself. We tested this possibility in Experiment 3 by using a tool which had no sharp edge, and which was held in such a way that the tip of the index finger lay somewhere along the shaft of the tool, i.e., at a location of the tool that did

not differ in saliency from any other part of the tool (see Fig. 1a, middle).

4. Experiment 3

4.1. Methods

Six volunteers (aged 21–28, mean 24; two women) received payment in exchange for their participation in Experiment 3. All had normal visual acuity and no known neurological disorders. None had participated in the previous experiments and all were naïve regarding the object of the experiment, except one author (T.C.). All gave their informed consent prior to starting the experiment, which was carried out according to the Declaration of Helsinki (2008).

Experiment 3 differed from Experiment 1 in the shape of the tool used to point to the targets. The tool was arc-shaped (Fig. 1a, middle). It was held with the index finger extended along the shaft of the tool; the fingertip lay somewhere along the shaft. This decoupled the location of a possibly salient angle in the tool from the fingertip. The relationship between finger and tool endpoint was identical to that of Experiment 1 (distance 8.4 cm at 45°). Therefore, all experimental parameters (stimuli sizes and relative positions) were identical to Experiment 1. All timing details were also identical, with the exception that the duration of discrimination target presentation was set at 170 ms for all participants (the average from Experiments 1 and 2).

Each experimental session consisted of 192 trials, where each combination of cued and DT location (upper, lower, left, right) was equiprobable and tested 12 times per session. As before, both distracters were present on each trial.

4.2. Results

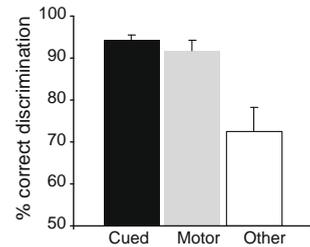
Fixation was monitored online and trials during which fixation was broken were rerun ($12 \pm 15\%$). Analysis of movement data was identical to the previous experiments and led to $4 \pm 2\%$ of data being discarded. Average movement latency was 720 ± 261 ms and duration 828 ± 99 ms.

Fig. 3a presents discrimination performance as a function of DT location (cued, motor or other) in Experiment 3. A one-factorial ANOVA confirmed that there was a main effect of DT location ($F(2, 10) = 13.5, p < 0.001$). DTs at the cued and motor endpoint locations were equally discriminated ($81 \pm 15\%$ and $77 \pm 13\%$, respectively) ($F < 1$) and both were better discriminated than DTs at other locations ($64 \pm 11\%$) ($F(1, 7) = 8.5, p < 0.025$; $F(1, 7) = 28.8, p < 0.002$).

4.3. Discussion

This experiment shows that the perceptual enhancement at the motor endpoint is related to planning the movement of the fingertip, and not to a salient feature of the tool. Perceptual enhancement was found when the index fingertip did not coincide with a potentially salient angle in the tool.

(a) Results – Curved tool (Exp. 3)



(b) Results – Little finger (Exp. 4)

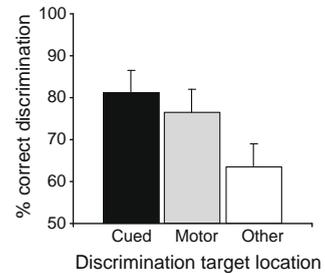


Fig. 3. Percent correct discrimination in Experiments 3 and 4, as a function of the discrimination target location (cued, motor, other). Error bars indicate s.e.m.

All experiments of the present study reported so far have assumed that the motor endpoint of the movement is the index fingertip. We provoked such a role of the fingertip by the specific way the tool was held. The index finger is of particular importance in many manual actions. For example, it is frequently used to point to objects, it is involved in the pinch grip and in actions that require a single finger to be used (see Ingram, Kording, Howard, & Wolpert, 2008, for statistical evidence of the index finger's special role in hand movements). The experience of this finger's importance may therefore lead to a habitual deployment of attention to the (planned) location of the index finger. In Experiment 4, we therefore asked if the movement endpoint during tool movement is always defined by the index finger, or if another finger can take on that role if the tool must be held in a different way. In Experiment 4, we examined whether the perceptual enhancement was observed at the motor endpoint location when the *little* finger was made more relevant for tool manipulation by placing it along the shaft of the tool (Fig. 1a, bottom).

5. Experiment 4

5.1. Methods

Eight volunteers (aged 21–28, mean 24; two women) took part in Experiment 4 in exchange for payment. All had normal visual acuity and no known neurological disorders. Four had participated in Experiment 3, including one author (T.C.). All gave their informed consent prior to starting the experiment, which was carried out according to the Declaration of Helsinki (2008).

The tool was mirror-reversed with respect to Experiment 1: the tip extended to the right of the little finger (Fig. 1a, bottom), which was extended along the shaft. The experimental parameters (stimuli sizes and relative positions) and timing details were identical to Experiment 3, with the exception that the entire display was shifted to the right. This was done so that the hand remained under the two-way mirror at all times (even when placing the tip of the tool of the leftmost target). Each experimental session consisted of 192 trials, where each combination of cued and DT location (upper, lower, left, right) was equiprobable and tested 12 times per session. As before, both distracters were present on each trial.

5.2. Results

Fixation was monitored online and trials during which fixation was broken were rerun ($24 \pm 16\%$). Analysis of movement data was identical to the previous experiments and led to $3 \pm 2\%$ of data being discarded, for each experiment, respectively. Average movement latency was 724 ± 312 ms and duration 862 ± 163 ms.

Fig. 3b presents discrimination performance as a function of DT location (cued, motor or other). A one-factorial ANOVA revealed a main effect of DT location ($F(2, 14) = 5.7, p < 0.001$). DTs at the cued and motor endpoint locations were equally discriminated ($94 \pm 3\%$ and $92 \pm 6\%$, respectively) and both were better discriminated than DTs at other locations ($73 \pm 14\%$).

5.3. Discussion

When the tool was held such that the little finger extended along the shaft of the tool, the perceptual enhancement was found at the tip of this finger. Thus, any motor planning-related perceptual enhancement does not seem to be linked only to the index finger but seems to be determined by the specific way a movement is carried out. In our experiment, the use of the little finger in directing the tool made that finger relevant for the task, and consequently lead to perceptual enhancement at its endpoint. Similarly, in Experiments 1–3, the index finger was more relevant for directing the tool, and a perceptual enhancement was thus allocated to its movement endpoint.

Experiments 1–4 demonstrated that attention is deployed specifically to two fine-tuned locations in space during the planning of a movement with a tool, namely to the endpoint of the tool tip as well as to the endpoint of the part of the hand (fingertip) which is most relevant in directing the tool. However, these experiments cannot answer the question if attention to these two points is deployed in parallel, or if attention is switched back and forth between them. Results from studies investigating the planning of serial movements indicate that attention is allocated simultaneously to all planned movement endpoints of the series (both saccadic eye movements and manual pointing movements; Baldauf & Deubel, 2008, *in press*; Baldauf et al., 2006). In a similar way, we tested if attention is allocated to both the movement goal and the motor endpoint in parallel. To this end, we asked par-

ticipants in Experiment 5 to perform a task which required comparing two concurrently presented targets. These could appear at the cued location, the motor location, or another location. The targets were displayed for a very short time only, too short for attention to switch between the two (Godijn & Theeuwes, 2003; Hahn & Kramer, 1998; Kramer & Hahn, 1995; VanRullen, Carlson, & Cavanagh, 2007). If attention is deployed serially, performance whatever the target locations should therefore be around chance level. In contrast, if indeed attention is deployed to both the goal and movement endpoints in parallel, participants should perform above chance when the targets were presented at the cued and motor locations, even with the very short presentation time of our experiment.

6. Experiment 5

6.1. Methods

Eight volunteers (aged 21–28, mean 24; three women) received payment in exchange for their participation. All had normal visual acuity and no known neurological disorders. Five had participated in Experiment 4, including one author (T.C.). All gave their informed consent prior to starting the experiment, which was carried out according to the Declaration of Helsinki (2008).

The stimuli and tool were identical to Experiment 1. However, participants performed a matching task based on that developed by Baldauf and Deubel (2008). Two of the four placeholders were replaced by targets (/ or \) and the two others by one horizontal and one vertical distracter. Participants had to report whether the two targets were similar (/ / or \ \) or different (\ /) by responding with the button box held in the left hand. Targets were presented for 80 ms, and DT presentation was followed by a 30 ms blank introduced to avoid floor effects due to stimulus masking. All other stimuli durations were identical to the previous experiments.

One experimental session consisted in 192 trials. Each combination of cued location and double-DT location was tested eight times per session.

6.2. Results

Fixation was broken during $26 \pm 17\%$ of trials; these were detected online and rerun. Analysis of movement data was identical to the previous experiments and led to $3 \pm 3\%$ of data being discarded. Average movement latency was 788 ± 267 ms, and duration was 868 ± 186 ms.

Fig. 4 presents matching performance as a function of the two DT locations. The two DTs could appear in the cued and motor endpoint locations, only one of these, or neither. A one-factorial ANOVA revealed a significant effect of DT location ($F(3, 21) = 11.5, p < .0001$). Performance when the DTs were at both the cued and motor endpoint locations was better than when only one DT was at the cued or motor endpoint location, and when the DTs were both at another location (all $ps < 0.03$). None of the other conditions differed significantly (all $ps > .25$).

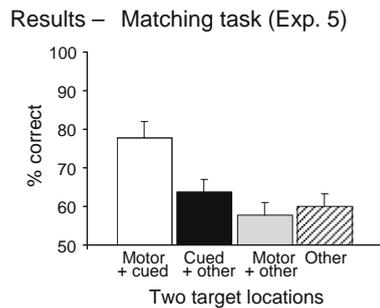


Fig. 4. Percent correct in the matching task (Experiment 5) as a function of the location of the two targets (both targets in cued and motor locations; one target in the cued location and one in another location; one target at the motor endpoint location and one in another location; both targets in other locations). Error bars indicate s.e.m.

6.3. Discussion

To perform the matching task correctly, attention must be oriented towards both target locations. Indeed, the brief presentation time (80 ms) precludes a serial shift of attention between the two locations. Therefore, matching performance should be better when the DTs are presented at the cued and motor endpoint locations only if attention is oriented to these locations in parallel. The results confirmed this hypothesis. This experiment, therefore, suggests that the two processes responsible for attentional allocation (selection of the target and the selection of the endpoint of the movement necessary to acquire it) occur at essentially the same time.

7. General discussion

Our results suggest that both goal selection and motor planning processes contribute to orienting visuo-spatial attention throughout the visual field during the preparation of a manual pointing movement. Perception was enhanced for the movement endpoints of those two objects that are most relevant during tool use – the fingertip and the active part of the tool. In contrast, perception was not enhanced at other spatial locations. Perception was high at the spatial location which was to be attained (the action goal or cued target location), but was also enhanced at the location towards which the hand holding the tool was about to be moved (the motor endpoint location). When we manipulate the environment with our own body, usually the hands, the goal location and the motor endpoint are identical, and perception is enhanced at this common spatial location (e.g., Deubel & Schneider, 2004; Deubel et al., 1998). For action planning with a tool, a perceptual enhancement at the location of the tool tip is useful as any changes at this location would call for a correction of the intended tool action. The second spatial location at which perception is enhanced during tool use seems to be the hand holding the tool, and in particular, the finger used to point the tool. On the motor level, it is the hand which executes the action, and any changes at this hand-tool interface location would also call for a revision of the movement plan.

These two locations appear to benefit from perceptual enhancement at the same time. In other words, visuo-spatial attention is not oriented first to the cued location, then to the motor location, but rather seems to be directed in parallel to both locations. Perceptual enhancement at both the motor endpoint and cued locations was found with a tool for which there was no salient corner at the motor endpoint and when the little finger extended along the tool handle. This implies that the benefit observed at the motor endpoint location cannot be explained as a consequence of the specific type of tool being used, nor as a consequence of the predominant role of the index finger in pointing in comparison to the other fingers of the hand.

Our study used a tool to dissociate goal selection from motor planning. Tool use itself has been extensively researched in recent years. Some neurons in the frontal and parietal lobes have tactile receptive fields (RFs) around the hand and visual RFs constricted to the space immediately around the tactile RF; this visual space around the body has been named peripersonal space (Graziano & Cooke, 2006; Rizzolatti & Luppino, 2001). When monkeys were trained to use a tool, these visual RFs of similar neurons in the intraparietal part of area PE (PEip) were extended along the shaft of the tool, suggesting an incorporation of the tool into the body schema (Iriki, Tanaka, & Iwamura, 1996). These findings have been related to experiments in humans which show that the interference of spatially incongruent visual stimuli on tactile localization is stronger when the visual stimuli are presented near the hand rather than in far space (Spence, Pavani, Maravità, & Holmes, 2004). When participants hold a tool near the (previously distant) distractor stimuli, distractor effects increase to a level similar to that of near distractors (Holmes, Sanabria, Calvert, & Spence, 2007; Holmes & Spence, 2004; Maravità, Spence, Kennett, & Driver, 2002). These findings have been interpreted as suggesting that the body schema was extended to include the tool. However, the visual-tactile interference in humans is confined to the tip of the tool and the hand, and does not include locations along the shaft of the tool (Holmes, Calvert, & Spence, 2004), suggesting shifts in multisensory spatial attention rather than an extension of the body schema (Holmes et al., 2007). Accordingly, event-related potential crossmodal visual attention effects are restricted to lights at the tip of a tool and the hand holding it during a tactile discrimination task in which tactile stimuli were applied to the hand (Yue, Bischof, Zhou, Spence, & Röder, in press). Our results are in accordance with these recent findings: an attentional enhancement was evident at the target locations that corresponded to the tool tip and to the hand, but not between these two locations. However, our experiment tested perception at locations near the future locations of the hand and tool. The mechanisms involved in such “predictive” perception might be different from those involved in perception within peripersonal space. Many studies have shown that visual receptive fields shift to a new location just before an eye movement (e.g., Duhamel, Colby, & Goldberg, 1992), a mechanism which could sub-tend the allocation of attention to the future endpoint. If such an updating mechanism existed for hand movements, one could speculate that the visual receptive fields responding

to the tool tip also shift before movement. In such a framework, the body schema itself could be updated just prior to movement.

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