Mental Space Maps into the Future

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Abstract: It has been suggested that our mind anticipates the future to act in a goal-directed, event-oriented manner. Here we asked whether peripersonal hand space, that is, the space surrounding one's hands, is dynamically and adaptively mapped into the future while planning and executing a goal-directed object manipulation. We thus combined the crossmodal congruency paradigm (CCP), which has been used to study selective interactions between vision and touch within peripersonal space, with an object manipulation task. We expected crossmodal interactions in anticipation of the upcoming, currently planned object grasp, which varied trial-by-trial depending on the object's orientation. Our results confirm that visual distractors close to the future finger positions selectively influence vibrotactile perceptions. Moreover, vibrotactile stimulation influences gaze behavior in the light of the anticipated grasp. Both influences become apparent partly even before the hand starts to move, soon after visual target object onset. These results thus support theories of event encodings and anticipatory behavior, showing that peripersonal hand space is flexibly remapped onto a future, currently actively inferred hand position.

Keywords: event segmentation theory; theory of event coding; anticipatory behavioral control; peripersonal space; cross-modal congruency paradigm

1. Introduction

Over the last two decades, various theories on "anticipatory behavior" suggest that our mind predicts immediate but also more distant future consequences of self-executed actions and perceived events and thus acts in an anticipatory, goal-directed manner (Friston, 2009; Friston, Daunizeau, & Kiebel, 2009; Hoffmann, 1993; Hoffmann, 2003; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Prinz, 1990). These theories imply that encodings of future states are activated before actual goal-directed motion takes place and that goal-directed, active inference processes focus the mind on those aspects that are believed to be critical for achieving a particular goal, such as a successful object grasp.

A recent theory extension (Butz, 2016) complements the event segmentation theory (EST) proposed in cognitive psychology (Zacks, Speer, Swallow, Braver, & Reynolds, 2007; Zacks & Tversky, 2001). EST suggests that our mind segments perceptions into events and event boundaries. For example, drinking from a bottle can be segmented into reaching, grasping, transporting, and actual drinking. Combined with anticipatory behavior, the extended theory suggests that our mind focuses on desired future event boundaries and subsequent events. For example, our eyes fixate an object when preparing an object grasp in such a way that the intended grasp type and the subsequent object manipulation can be inferred (Belardinelli, Stepper, & Butz, 2016).

Furthermore, it has been proposed that event boundaries will typically involve spatial predictive encodings, which characterize when an event boundary is likely to occur (Butz, 2016). Thus, anticipatory spatial remappings towards upcoming event boundaries can be expected to be present even before the actual goal-directed action towards that event boundary unfolds. Interestingly, event-oriented segmentations are well-suited for enabling hierarchical planning and motor control (Botvinick, Niv, & Barto, 2009; Botvinick & Weinstein, 2014; Wolpert, Diedrichsen, & Flanagan, 2011) and they offer an explanation of how event encodings (Hommel et al, 2001) may develop.

In this work, we asked whether the peripersonal space (PPS) surrounding one's hands is mapped into the future onto the next anticipated event boundary, that is, an object grasp. Behavioral neuroscience has indicated that PPS encodes the space surrounding bodily surfaces, such as the hand or the face, regardless of where the surface is currently positioned, integrating all relevant multisensory information available (di Pellegrino, Làdavas, & Farnè, 1997; Fogassi, Gallese, Fadiga, Luppino, Matelli, & Rizzolatti, 1996; Holmes & Spence, 2004; Làdavas, Zeloni, & Farnè, 1998). Moreover, it has been proposed that PPS encodings exist for enabling effective spatial interactions (Graziano & Cooke, 2006). While typically being anchored to a body part, it was shown that PPS partially remaps around a tool upon tool usage (Holmes, 2012).

One means to explore multimodal sensory interactions in PPS is the crossmodal congruency paradigm (CCP; see e.g. Spence, Pavani, Maravita, & Holmes, 2004), where task-irrelevant visual stimuli interfere with tactile perceptions if the former are presented close to the tactually stimulated body part. Typically, participants are slower and less accurate in identifying whether the thumb or the index finger was stimulated if concurrently a LED is flashed at the other finger location (incongruent condition), whereas a flash at the location of the stimulated finger prompts a faster response (congruent condition). In the case of a concurrent grasping task, vision-to-touch interference can actually occur at a distance – before the hand gets close to the target object – when visual stimuli are presented on the object, even at the time the hand just starts to move (Brozzoli, Pavani, Urquizar, Cardinali, & Farnè, 2009; Brozzoli, Cardinali, Pavani, & Farnè, 2010). These results emphasize the importance of PPS encodings for executing manipulative interactions (Brozzoli, Makin, Cardinali, Holmes, & Farnè, 2012; Brozzoli, Ehrsson, & Farnè, 2014). In previous studies, however, the required (pinch) grasp was instructed and thus predictable. Moreover, the object was always visible to the participants throughout the trial, and thus also already before the go signal for the motor task. As a result, the congruent configurations were fixed and the role and adaptivity of the spatial mapping remained elusive.

We thus asked if PPS is adaptively remapped into the future in anticipation of the next event boundary and subsequent event, that is, the intended grasp followed by an object manipulation. We expected to observe an anticipatory crossmodal congruency effect (aCCE), in which visual distractors near the future finger position at the to-be grasped object should affect responses to tactile vibrations on the fingers depending on the planned grasp type. Moreover, we reasoned that an eye gaze preference towards that object side where the stimulated finger would be placed should be detectable. While effects of touch on visual perception have been reported for static and moving visuo-tactile stimuli (Driver & Spence, 1998; Gray & Tan, 2002), to the best of our knowledge, no haptics-related oculomotor effects have been reported in anticipation of an upcoming hand-object interaction.

To investigate the hypothesized aCCE, we combined CCP with an object manipulation task: participants had to reach and virtually grasp a bottle on a touchscreen, displace it slightly to the right, and put it back down in an upright orientation. Additionally, participants had to verbally report the finger (thumb or index) on which a vibrotactile stimulation was felt. Concurrently with the vibration, sometimes a visual distractor was presented on one side of the bottle about where the thumb or index finger would be placed.

The critical manipulation was the variation of the bottle's orientation at visual onset – either upright or upside-down – calling for different hand-grasp orientations – either overhand or underhand – in anticipation of the intended manipulation (Herbort & Butz, 2011; Herbort & Butz, 2012; Rosenbaum, Marchak, Barnes, Siotta, & Jorgensen, 1990; Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012). Critically, the two grasp types yield different crossmodal congruencies, seeing that the index finger (thumb) will be placed on the right (left) or left (right) side of the bottle, depending on whether the bottle is presented upright or upside down (see Fig. 1). In this case, hence, congruency is flexibly defined according to the unfolding motor planning, which can be decided only once the target object is shown (i.e upon visual onset). Furthermore, to investigate the dynamics of such an anticipatory PPS remapping, the visuo-tactile stimulation was applied at different points in time around movement onset and two complementary experiments were conducted. Taken together the results show that PPS is indeed mapped highly adaptively and purposefully into the future supporting the upcoming and unfolding motor behavior.

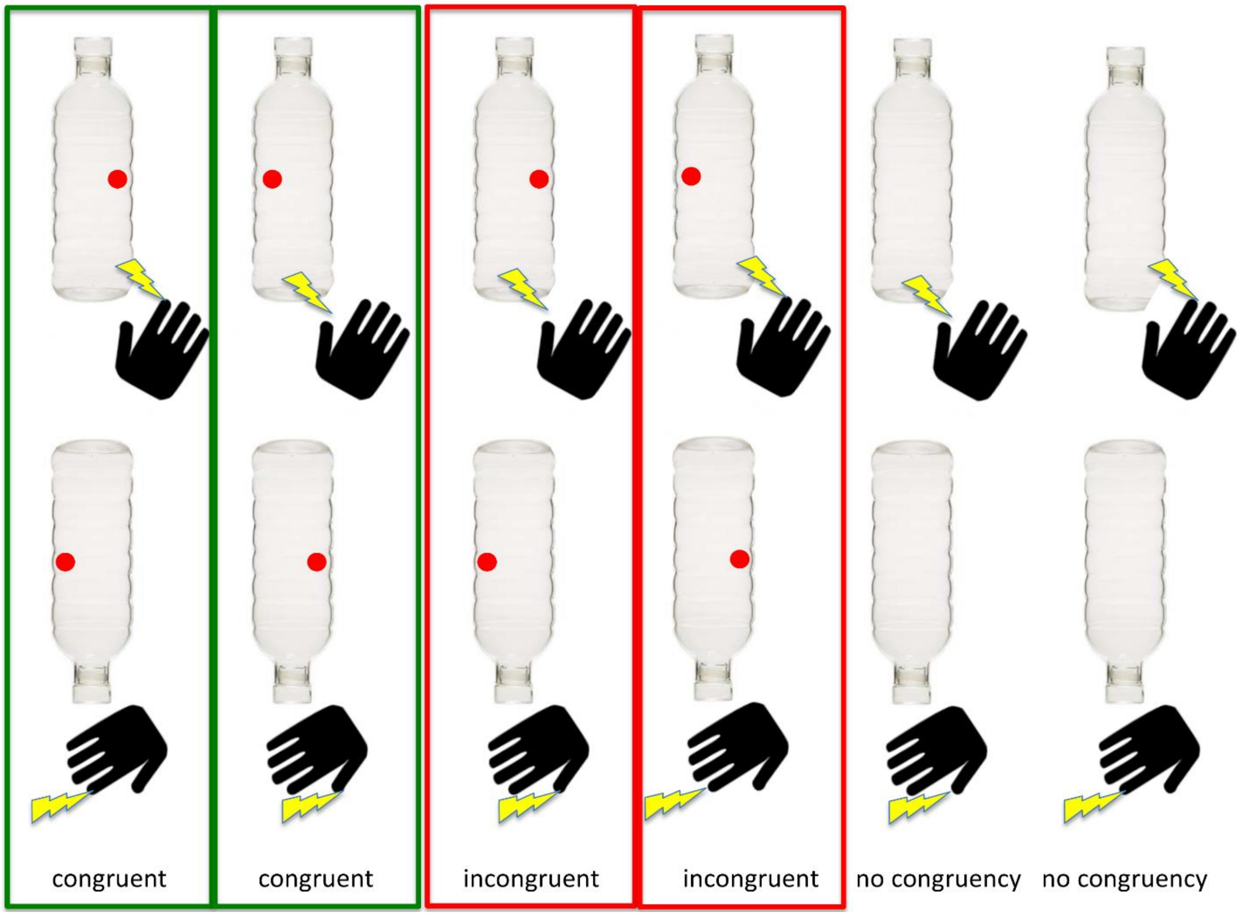

Fig. 1. Trial conditions of upright and upside-down bottles with respect to visual distractor (red dot) and vibrotactile stimulations (yellow flash). Left two columns (green boxes), center two columns (red boxes), and right two columns, show congruent, incongruent, and no visual distractor conditions, respectively.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Sixteen participants (*M* = 24.9, *SD* = 4.9 years, 8 female) took part in the experiment. Three participants (2 female) were excluded because of bad quality eye-tracking data. The sample size was determined comparable to that of previous studies in the literature on CCE (e.g., Brozzoli et al., 2010). All participants were right-handed, had corrected-to-normal vision, and reported normal tactile sensitivity. They were compensated for their participation with money or course credit and signed the informed consent form. The experiment was carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki.

2.1.2. Apparatus

The visual target stimulus used in both experiments was a picture (320 x 960 pixel, 7.1° x 22.1°) of a 0.5 l plastic bottle full of water on a white background. Stimulus presentation was done on a 1680 x 1050 pixel (37.1° x 24.2°) touchscreen with a refresh rate of 60 Hz.

A red dot (10 pixel, 0.23° radius) was used as visual distractor and presented (in the corresponding conditions) for 200 ms either on the right side or the left side 80 pixel (1.84°) away from the center and at middle height on the bottle. The simultaneous tactile stimulation was delivered to the acting hand by means of LilyPad Arduino vibration motors (2.0 cm diameter, 0.8 cm thickness), applying a vibration for 200 ms to either the thumb or the index fingertip. The motors were controlled via an Arduino Uno microcontroller (Arduino S.R.L.) running custom C software.

Eye movements were collected by means of a binocular remote eyetracker (EyeFollower, LC Technologies), working at 120 Hz and with an accuracy <0.4° even under head movements. Each participant was calibrated with a 9-point calibration procedure.

A keyboard was placed between the participant and the monitor to record reaction times. Participants had to hold down the space bar to start the next trial, releasing it when initiating the reach towards the bottle. Motion times were measured as the time between space bar release and first touch on the touchscreen. Additionally, the touchscreen information was used to confirm the grasp type.

Verbal responses were collected via a headset microphone using a custom C# program, based on the Microsoft Speech API 5.4. The API provides a time-stamp at the beginning of each utterance.

The whole experiment was implemented in Matlab R2013a, using the Psychophysics Toolbox extension (Brainard, 1997).

2.1.3. Design and procedure

Participants sat at a table in front of the apparatus and at about 70 cm from the screen. The experiment consisted in a dual task paradigm. As a first task, participants were requested to fixate a fixation cross on the left of the screen 420 pixel (9.3°) away from the center of the screen and to keep their right hand on the spacebar until the stimulus appeared in the center of the screen. Upon stimulus presentation they had to plan the grasp and displacement of the bottle on the screen to a target location on the right side of the screen, (420 pixel, 9.3° away from the center), denoted by a flat gray ellipse. The grasp was detected by the first touch on the screen and determined the disappearance of the bottle picture. A second touch on the right half of the screen was considered as the placing of the bottle on the target location (and determined its reappearance there). The return of the hand to the spacebar signaled the end of the trial (see Fig. 2 for an exemplary trial time course). The bottle could be presented either upright or upside down (factor orientation). Participants were instructed to grasp the bottle and place it back in an upright orientation, so to enforce a supine (underhand) grasp when the bottle was presented upside down.

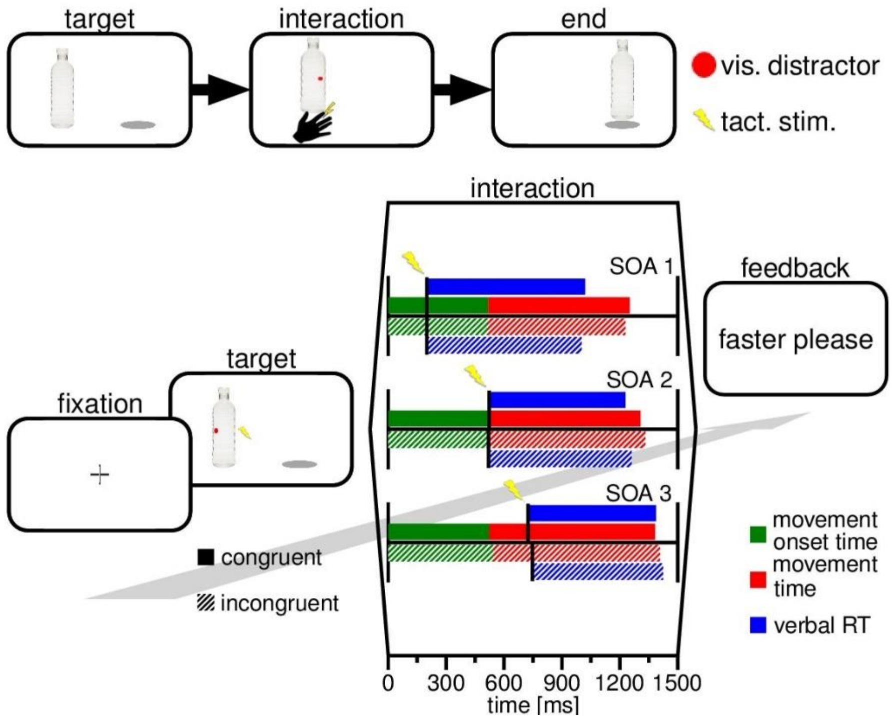

Fig. 2. Mean time course of a trial in Experiment 1. Top: After visual onset of the bottle, which could be presented either upright or upside down, participants had to move their hand towards the bottle shown on the screen, pretend to grasp the bottle by making contact with the touch screen, and move the bottle to the indicated position on the right, turning it upright if necessary. Bottom: During the trial, tactile (denoted as a yellow flash) and optional visual stimulation (red dot) were delivered concurrently either 200 ms after visual onset of the bottle (SOA1), at motion onset (SOA2), or 200 ms after motion onset (SOA3). The possible feedback at the end of the trial indicated whether the interaction was successful (bottle correctly grasped) or if a faster verbal response was required – ensuring that both the bottle transportation task and the tactile stimulus identification task were attended. The bars in the plot for the three SOAs represent mean values for the hand motion onset (green), the verbal response time after stimulation (blue), and the movement time from motion onset up to the first touch on the touchscreen (red). Solid bars are for congruent conditions (same side of the bottle for the visual distractor and the final position of the stimulated finger), dashed bars are for incongruent conditions.

The second, concurrent task was to discriminate which finger received a vibrotactile stimulation at some point during the trial and to promptly report the stimulated finger verbally (saying “index” or “thumb”, i.e., in German “Zeigefinger” or “Daumen”) upon vibration detection.

The crossmodal visuo-tactile stimulation was delivered at different time points after the stimulus presentation (factor SOA, see Fig. 2): 200 ms after stimulus onset (SOA1), at hand movement onset (SOA2), or 200 ms after movement initiation (SOA3). In one third of the trials the visual distractor appeared on the right side, in one third on the left side, and in one third no visual distractor was presented (factor visual distractor side). In half of the trials, the tactile stimulation was delivered to the tip of the thumb and in half to the index fingertip (factor stimulated finger). The 2 (bottle orientation) x 3 (visual distractor side) x 2 (stimulated finger) x 3 (SOA) factor combinations were repeated 3 times, resulting in 108 trials, which were preceded by 12 random practice trials. If no response was given within 2 s from the tactile stimulation or if the bottle was grasped with the wrong grasp (depending on the orientation) the trial was repeated. Figure 1 shows the trial-by-trial manipulations and the resulting cross-modal congruency conditions.

The whole experiment lasted about 40 min.

2.1.4. Dependent Measures

Verbal response times with respect to the tactile stimulation and gaze positions were collected as primary dependent measures. They were used to determine the strength and dynamics of the expected aCCE throughout the respective trials.

With respect to the gaze data, we focused on the horizontal axis (x-axis), since we expected this axis to be more affected by the experimental manipulation. We considered eye position samples up to 600 ms after the crossmodal stimulation had been delivered. This time was further analyzed within windows of 300 ms (0-300, 100-400, 200-500, 300-600 ms). (x,y) positions are the most reliable position data, both in spatial and temporal terms (discounting the device precision and accuracy), which we used to find a temporal window, aligned across participants, where manipulation effects would be most evident. When the stimulation occurred during the reaching movement, the hand was often already further on its way to the screen, hence occluding one of the eyetracker cameras. For this reasons our analysis focusses on the first two SOAs. Effects regarding the gaze position were most pronounced in the fourth bin (300-600 ms after vibrotactile stimulation), building up systematically towards that bin. Thus, to focus the description, we report only results from this bin.

We also recorded the movement onset time as the time between the appearance of the bottle and movement initiation. This was merely a control variable to check whether verbal and manual response interacted

Gaze and response time data are available at the Open Science Framework (https://osf.io/8pgjn/).

2.2. Results

Regarding our hypotheses, we were mostly interested in an aCCE with respect to verbal response times. Generally, we expected that the aCCE would be measurable in the three-way interaction between bottle orientation, visual distractor side, and stimulated finger, with possible further dependence on the SOA. Accordingly, verbal response times were analyzed with a repeated measures ANOVA according to the 2 (bottle orientation) x 3 (visual distractor side) x 2 (stimulated finger) x 3 (SOA) design. Furthermore, to analyze the aCCE more directly, we calculated the response times differences between incongruent and congruent conditions. That is, for each combination of SOA and bottle orientation, we obtained a response time difference between the incongruent and congruent combination of the visual distractor side and stimulated finger factors, depending on the bottle orientation (see Fig. 1).

With respect to gaze behavior, an aCCE cannot be determined. Rather, the interaction between stimulated finger and bottle orientation was of central interest. We expected that a systematic bias of the gaze towards the anticipated position of the stimulated finger on the bottle should yield such an interaction. Moreover, we were interested in the time course of such an interaction and possible interactions with the visual distractor. Thus, also gaze positions were analyzed with a repeated measures ANOVA according to the 2 (bottle orientation) x 3 (visual distractor side) x 2 (stimulated finger) x 3 (SOA) design.

All reported post-hoc comparisons were submitted to a Bonferroni correction. If the assumption of sphericity was violated, the respective *F*- and *p*-values were submitted to a Greenhouse-Geisser correction.

2.2.1. Verbal Response Times

For this analysis we considered only trials in which participants correctly identified the stimulated finger (96.8 % of all trials) and focused on the trials in which a visual distractor was presented. There was a main effect of SOA ($F(2, 24) = 20.02$, $p < .001$), such that the verbal response times decreased with SOA (M_{SOA1} = 811 ms, M_{SOA2}= 723 ms, M_{SOA3}= 669 ms). More importantly, the four-way ANOVA yielded the expected interaction of bottle orientation, visual distractor side, and stimulated finger ($F(1,12) = 21.38$, $p = .001$), confirming the presence of a flexible remapping of PPS. This interaction is shown in the central plots of Fig.3, while its significance across SOAs is detailed in Fig. 4. Note that this analysis entailed other effects and was further complemented by the analysis of trials without distractors, but for the sake of readability we report the full details of these analyses in the Appendix.

The two-way ANOVA focusing on the aCCE yielded a significant intercept (grand mean = 46 ± 10 ms, $F(1,12) = 21.79$, $p = .001$). Hence, there was a general advantage for congruent conditions. This aCCE was independent of the factors SOA and bottle orientation (all other *p's* ≥.258). Fig. 4 details these results, indicating the SOA conditions in which the aCCE was significantly larger than 0.

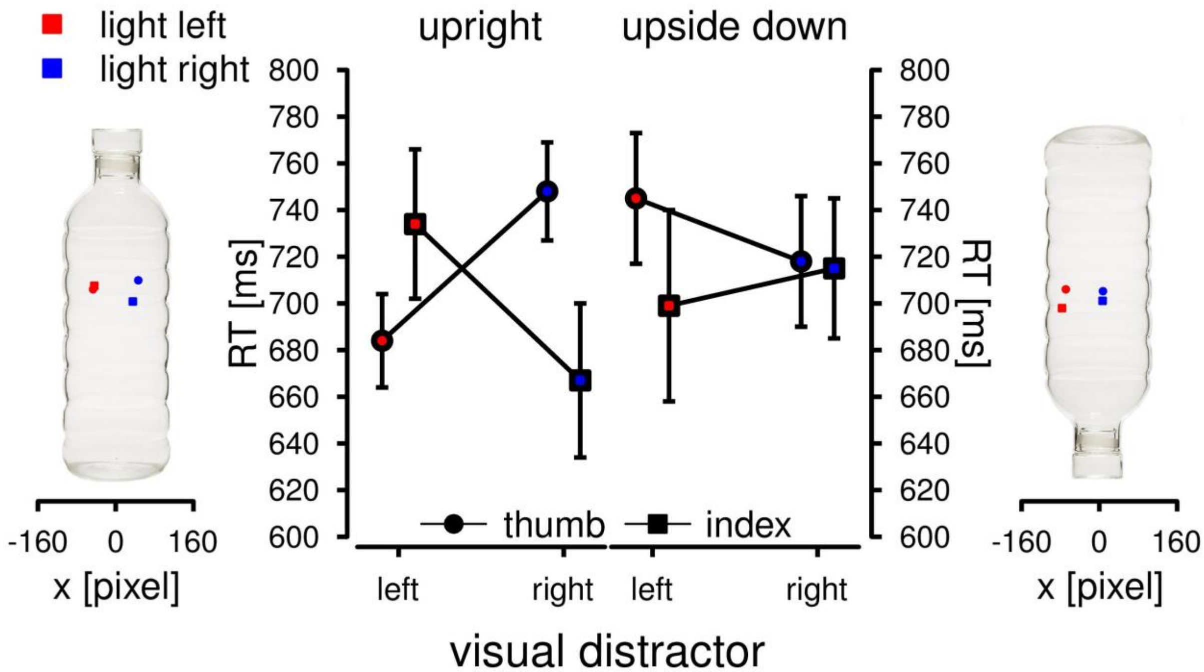

Fig. 3 Response times and mean gaze locations for Experiment 1. Central plots: verbal response times for the interaction of visual distractor and tactile finger stimulation depending on the bottle orientation. The left and right plots show the mean eye location in the time window 300-600 ms after stimulation depending on the side of the visual distractor, the stimulated finger (round marker for the thumb, square for the index), and the bottle orientation. Error bars show s.e.m.

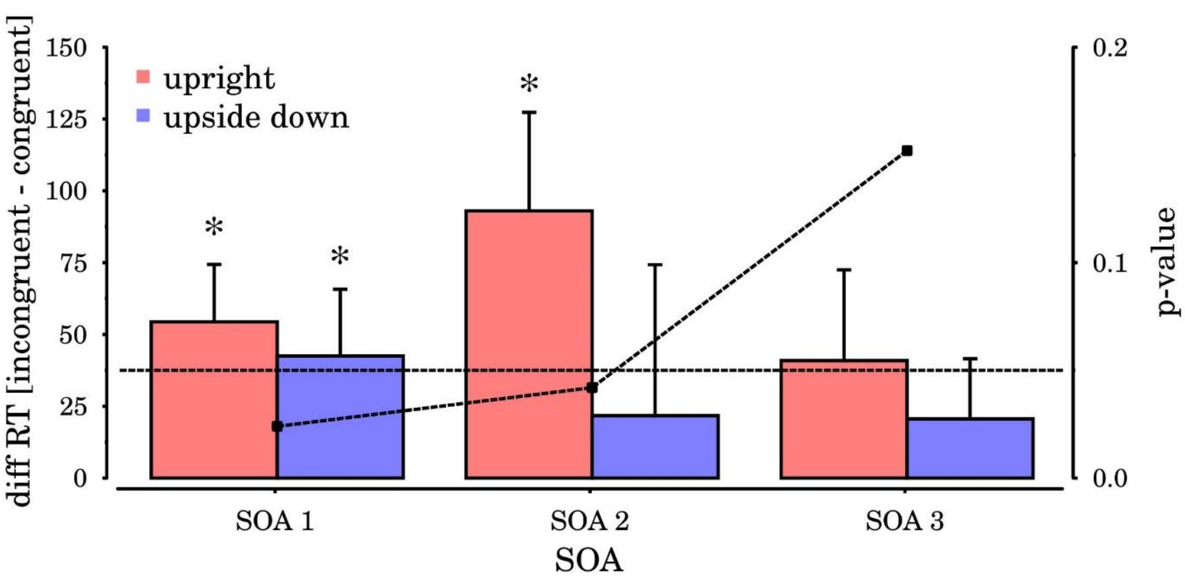

Fig. 4. Congruency effects in the different SOA conditions (SOA1: 200 ms after visual onset of the bottle; SOA2: at hand movement onset; SOA3: 200 ms after movement initiation) in Experiment 1, showing

means and s.e.m. Congruency effects were obtained as differences in milliseconds in response times between congruent and incongruent conditions per bottle orientation. Positive values indicate an advantage for congruent stimulation. For the upright bottle, vibrotactile stimulation of the index finger in conjunction with a visual distractor on the right side was considered congruent, likewise vibrotactile stimulation of the thumb in conjunction with a visual distractor on the left was considered congruent. For the inverted bottle, these were the two incongruent conditions. Conditions in which the advantage for congruent stimulation was significantly larger than zero are indicated by an asterisk. Square markers indicate the p-value of the three-way interaction of orientation, visual distractor side, and stimulated finger in the respective SOA condition in the four-way ANOVA reported in the Appendix. The horizontal dashed line indicates the α-level of .05.

2.2.2. Gaze Position

The gaze data analysis for the 300-600ms bins yielded significant main effects for bottle orientation ($F(1, 12) = 17.26$, $p = .001$) and visual distractor side ($F(2, 24) = 66.89$, $p < .001$). Participants focused more on the right side, when the bottle was presented upright and when the visual distractor was presented on the right side. Furthermore, the hypothesized interaction between bottle orientation and stimulated finger was significant ($F(1, 12) = 6.51$, $p = .025$). Participants looked more to the right when the index finger instead of the thumb was stimulated in the upright condition, and more to the left when the index finger instead of the thumb was stimulated in the upside down condition. Moreover, the three-way interaction between bottle orientation, visual distractor side, and stimulated finger was significant ($F(2, 24) = 6.20$, $p = .007$), suggesting that the visual distractor interfered with the vibrotactile influence on gaze behavior. Additionally, a significant interaction of SOA and visual distractor side was identified ($F(2, 24) = 5.21$, $p = .013$): the visual distractor influenced gaze behavior more strongly in early stimulation trials than in late stimulation trials.

To control for the observed effect of the visual distractor on the influence of the vibrotactile simulation on oculomotor behavior, we analyzed the trials without visual distractor separately. The respective three-way ANOVA (bottle orientation x stimulated finger x SOA) yielded a main effect of bottle orientation ($F(1, 12) = 10.85$, $p = .006$; $M_{\text{up}} = 140.1$ px, $M_{\text{down}} = 116.1$ px) and the interaction of bottle orientation and stimulated finger ($F(1, 12) = 11.92$, $p = .005$). When the bottle was presented upright, the eyes moved more to the right when the index finger instead of the thumb was stimulated. This interaction is depicted in Fig. 5. Indeed, when focusing this analysis on the first SOA only, the effect of bottle orientation ($F(1,12) = 5.08$, $p = .044$, $\eta_p^2=.298$) is actually weaker than the interaction between bottle orientation and stimulated finger ($F(1,12) = 6.12$, $p = .029$, $\eta_p^2=.338$), indicating that the finger vibration influences the eyes in anticipation of the upcoming grasp from very early on.

On the other hand, when analyzing the trials with visual distractor separately, the three-way interaction between orientation, visual distractor, and finger remained borderline significant ($F(1, 12) = 4.70$, $p=.050$, see also left and right panel of Fig.3). Thus, it remains uncertain whether the vibrotactile stimulation influences gaze behavior even during trials with visual distractor.

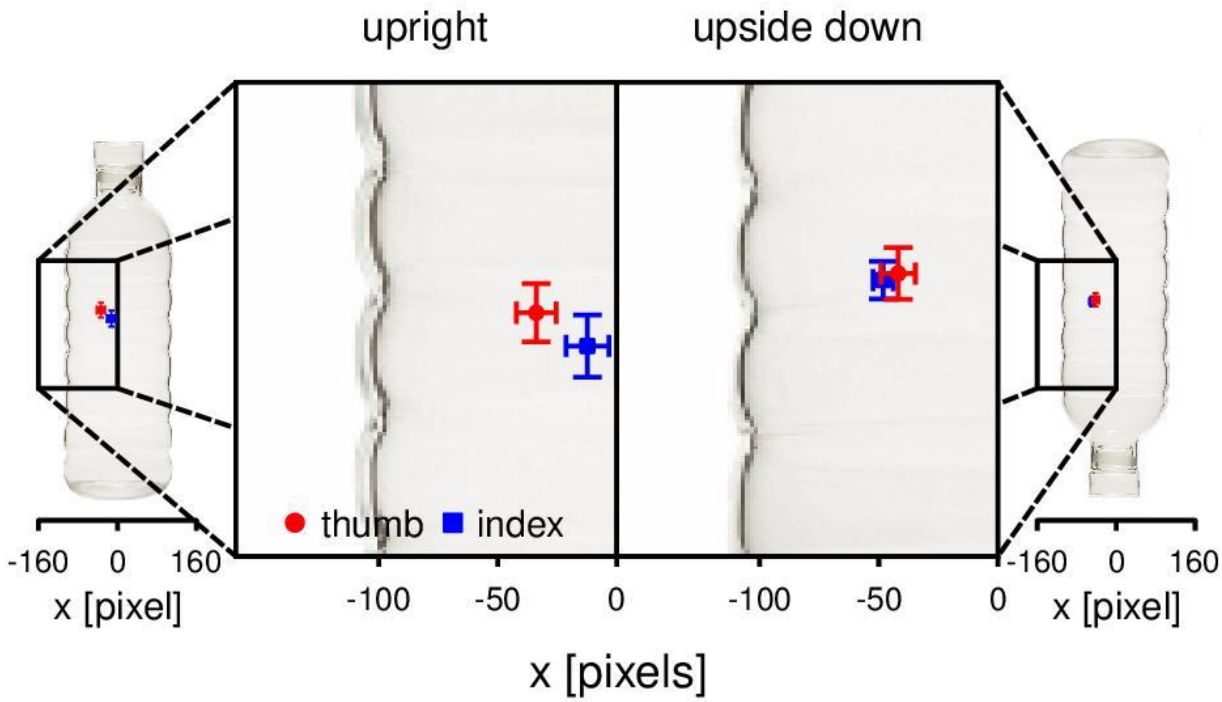

Fig. 5. Significant influence of the tactile stimulation on the gaze behavior depending on the orientation of the bottle and the stimulated finger in the trials without visual distractor in Experiment 1. In a time window of 300 ms, starting 300 ms after tactile vibration onset, the eyes looked more towards the side where the stimulated finger was going to be placed. Error bars show s.e.m.

2.2.3. Movement Onset Times

The analysis of manual reaction times was carried out considering only orientation and SOA as factors influencing movement onset. The 2x3 repeated measures ANOVA showed just a main effect of SOA ($F(2,24) = 4.36$, $p = .024$). Movement initiation was faster for earlier stimulation ($M_{SOA1} = 512$ ms; $M_{SOA2} = 524$ ms; $M_{SOA3} = 545$ ms), which suggests that the stimulation prompted the motor response initiation. Fig. 1 provides an overview of the overlap between manual and verbal responses.

3. Experiment 2

In order (i) to generally replicate the findings, and (ii) to answer the question whether the vibrotactile stimulus can influence gaze behavior even in trials with visual distractor, we ran a second experiment with more participants. Moreover, in order to exclude potential influences of the trials without visual distractors onto the trials with visual distractor and to further examine the time course of the aCCE, we left out the conditions without visual distractor and expanded the SOA levels to even earlier points in time.

To get an estimate of the number of participants that would be necessary to yield sufficiently reliable results as to the interaction between orientation and stimulated finger in the gaze behavior even when the visual distractor is present, we conducted a power analysis considering the smallest effect size from Experiment 1 (bottle orientation times stimulated finger over all three visual distractors and all three SOAs, which yielded p=.025, η_p^2=.35). With a power of .9 and an alpha level of .05, a lower bound for the sample size of 22 was determined. The power analysis was conducted by means of MorePower 6.01 (Campbell & Thompson, 2012). We thus aimed for slightly more than 22 participants, seeing that bad quality eye-tracking data typically occurs in some participants.

3.1. Methods

3.1.1. Participants

Twenty-eight participants (*M* = 23.8, *SD* = 3.9, 22 female) took part in the second experiment. One (female) participant was excluded because of bad quality eye-tracking data. All participants were right-handed, had corrected-to-normal vision and reported normal tactile sensitivity. They were compensated for their participation with money or course credits and signed the informed consent form. The experiment was carried out in accordance with the provisions of the World Medical Association Declaration of Helsinki.

3.1.2. Apparatus

The same apparatus and stimulus material were used.

3.1.3. Design and procedure

The procedure of the second experiment was in principle the same as the one in the first experiment, except for three notable differences. First, the fixation cross was shown in the center of the screen, such that, once it disappeared, participants were already fixating the bottle's center. Thus, no saccade was necessary to bring the gaze onto the object. Second, a visual distractor was presented in all trials. Third, a finer exploration of the temporal unfolding of the remapping was implemented by using five SOAs: in a first condition the vibrotactile stimulation was delivered already during the fixation cross presentation shortly before the bottle appeared (i.e. 150 ms prior to it); the second and third condition were to explore the time course further, applying the vibrotactile stimulus 50 ms and 250 ms after the presentation of the bottle; finally, the last two SOAs were chosen in accordance with the first experiment, that is, at hand motion onset and 200 ms into hand movement. An exemplification of a trial course, along with average reaction, response, and movement times in the different SOAs is depicted in Fig. 6.

The 2 (bottle orientation) x 2 (visual distractor side) x 2 (stimulated finger) x 5 (SOA) factor combinations were repeated 3 times each, resulting in 120 trials, preceded again by 12 practice trials. The whole experiment lasted about 45 minutes.

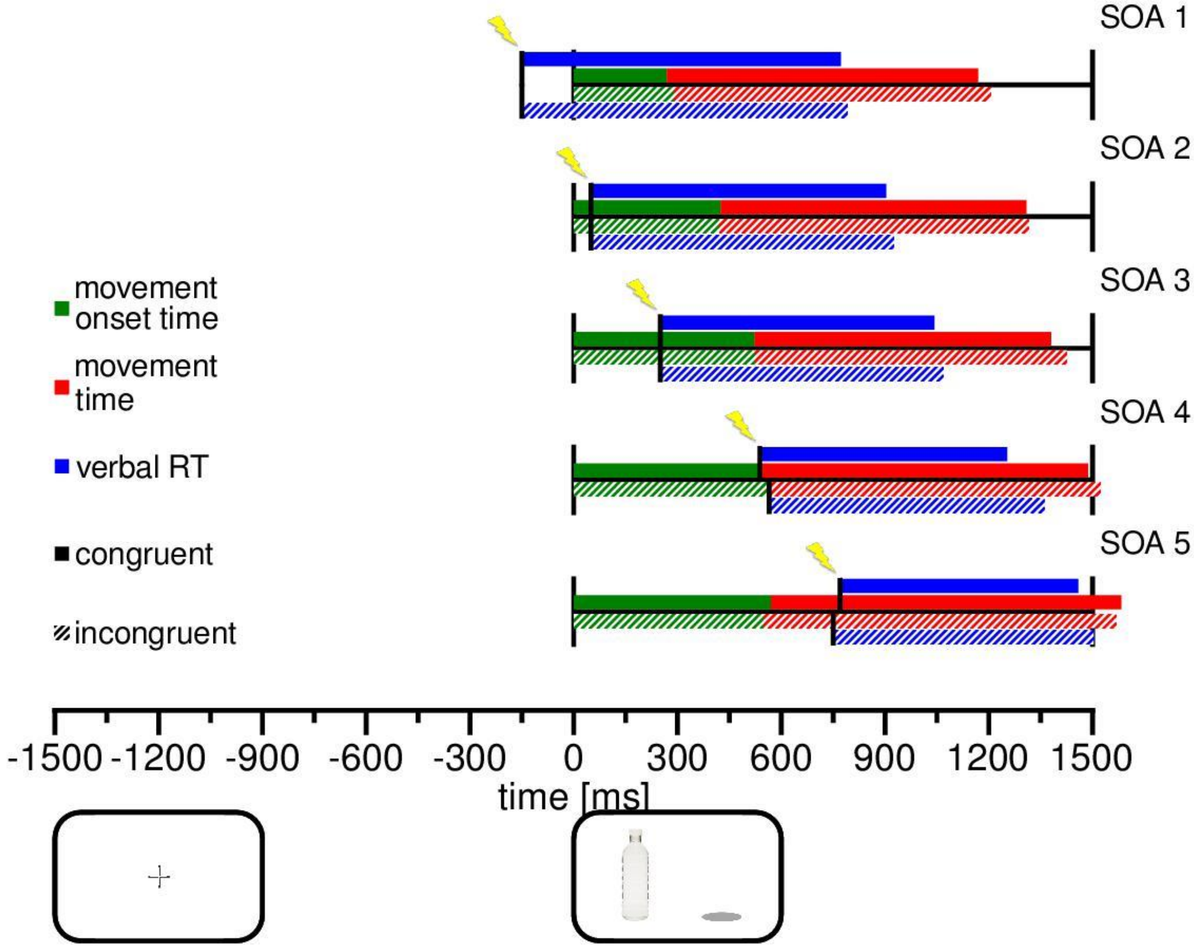

Fig. 6. Mean time course of trials in Experiment 2. During the trial, tactile (denoted as a yellow flash) and concurrent visual stimulation took place either 150 ms before visual onset of the bottle (SOA1), 50 ms after visual onset (SOA2), 250 ms after visual onset (SOA3), at motion onset (SOA4), or 200 ms after motion onset (SOA5). The possible feedback at the end of the trial indicated if the interaction was successful (bottle correctly grasped) or if a faster verbal response was required – ensuring that both the bottle transportation task and the tactile stimulus identification task were attended. The bars in the plot for the five SOAs represent mean values for the hand motion onset (green), the verbal response time after stimulation (blue), and the movement time from motion onset up to the first touch on the touchscreen (red). Solid bars are for congruent conditions (same side of the bottle for the visual distractor and the final position of the stimulated finger), dashed bars are for incongruent conditions.

3.1.4. Dependent Measures

As in the first experiment, we collected verbal response times and gaze positions. For the gaze data we again focused on the time window between 300 ms and 600 ms after vibrotactile stimulation. Moreover, we again recorded movement onset times.

3.2. Results

As in Experiment 1, verbal response times and gaze positions were analyzed with repeated measures ANOVAs according to the 2 (bottle orientation) x 2 (visual distractor side) x 2 (stimulated finger) x 5 (SOA) design. Moreover, response times were analyzed with an aCCE-focused analysis, using the difference between respective incongruent and congruent conditions as dependent measures. Again, all reported post-hoc comparisons were submitted to a Bonferroni correction. If the assumption of sphericity was violated, the respective *F*- and *p*-values were submitted to a Greenhouse-Geisser correction.

3.2.1. Verbal Response Times

For this analysis we considered only trials in which participants correctly identified the stimulated finger (98.1 % of all trials). The results from the four-way ANOVA replicate the results from the first experiment. Most importantly, the interaction of orientation, distractor side, and finger – denoting the presence of the aCCE – was significant ($F(1,26) = 41.23$, $p < .001$). Significance across SOAs is reported in Fig. 7. This analysis entails other effects and was further complemented by separate analysis of each SOA, the details of which we report in the Appendix.

Considering the aCCE-focused analysis, the two-way ANOVA with factors orientation and SOA revealed a main effect of SOA ($F(4, 104) = 3.24$, $p = .015$), whereby the aCCE measure grows from SOA 1 to SOA 4 and slightly declines in SOA 5 (M_{SOA1} = 20 ms, M_{SOA2}= 22 ms, M_{SOA3}= 25 ms, M_{SOA4}= 80 ms, M_{SOA5}= 64 ms). As in Experiment 1, the analysis yielded a significant intercept (grand mean = 42 ± 7 ms, $F(1,26) = 41.23$, $p < .001$), indicating a general, significant advantage in case of congruent stimulation. Fig. 7 shows these results and indicates when the aCCE reached significance with respect to each SOA. Experiment 2 thus generally replicates the results of the first experiment, even though the aCCE did not reach significance at SOA3 (which is comparable to SOA1 in the first experiment). It appears that the setup in this experiment with even earlier SOAs slightly delayed the build-up of the anticipatory PPS remapping – albeit qualitatively the aCCE is visible at SOA3, and partially even before that (compare results in Fig. 4 and Fig. 7).

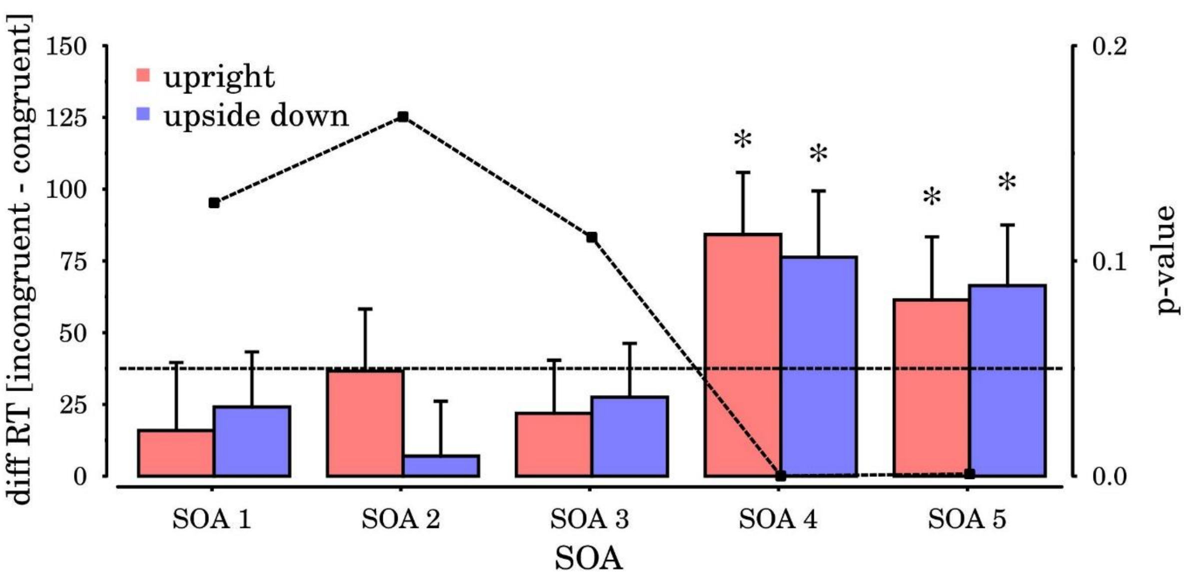

Fig. 7. Anticipatory crossmodal congruency effects in the different SOA conditions in Experiment 2, showing means and s.e.m. In this case the visuo-tactile stimulation was administered at five possible times: 150 ms before stimulus presentation (SOA1), 50 and 250 ms after stimulus onset (SOA2 and SOA3), at hand motion onset (SOA4), and 200 ms into movement (SOA5). Congruency effects were again obtained in terms of differences in response times between incongruent and congruent stimulations per bottle orientation. Conditions in which the advantage for congruent stimulation was significantly larger than zero are indicated by an asterisk. Square markers indicate the p-value of the three-way interaction of orientation, visual distractor side, and stimulated finger in the respective SOA condition, the horizontal dashed line indicates the α-level of .05.

3.2.2. Gaze Position

As in the first experiment, we focused the analysis on the time window between 300 ms and 600 ms after vibrotactile stimulation. The analysis yielded main effects for bottle orientation ($F(1, 26) = 47.73$, $p < .001$), visual distractor side ($F(1, 26) = 154.02$, $p < .001$), and SOA ($F(2.74, 71.27) = 3.40$, $p = .026$). Participants focused more on the right side, when the bottle was presented upright ($M_{up} = 179.1$ px vs. $M_{down} = 143.3$ px). Furthermore, a distractor on the right side biased the gaze position more to the right side ($M_{right} = 194.7$ px vs. $M_{left} = 127.7$ px). Over the different SOAs, the gaze shifted slightly leftwards ($M_{SOA1} = 165.9$ px, $M_{SOA5} = 158.7$ px). As in the first experiment, there was a significant interaction between bottle orientation and stimulated finger ($F(1, 26) = 4.27$, $p = .049$). Participants' gaze was biased to the right if the index finger was stimulated and the bottle was presented upright compared to trials were the thumb was stimulated. Furthermore, the two-way interaction between SOA and visual distractor side observed in the first experiment was significant again ($F(2.98, 77.60) = 26.38$, $p < .001$): eye focus was further to the right when the distractor appeared on the right side than when it appeared on the left and this effect was most pronounced in the second SOA. In contrast to the first experiment, the three-way interaction between bottle orientation, visual distractor side and stimulated finger showed a similar tendency as in the first experiment but did not reach significance ($F(1, 26) = 3.94$, $p = .058$).

Compared to the first experiment, the SOA condition strongly affected the pattern of results, reflected in two additional significant interactions involving the SOA. First, the interaction between SOA and bottle orientation was significant ($F(1.95, 50.63) = 29.03$, $p < .001$): the later the stimulation the closer the gaze was to the anticipated side of the index finger. Second, the three-way interaction between SOA, bottle orientation, and visual distractor was significant ($F(2.76, 71.73) = 3.83$, $p = .006$). Over the SOAs, the eyes were moving increasingly in the direction of the visual distractor if the distractor was on the side of the index finger. If the distractor was on the thumb's side, the eyes moved in that direction in earlier stimulation, but went more to the index finger side in the later SOAs.

Given the stronger effects of the SOA compared to the first experiment, we complemented this analysis with two further ANOVAs, one just for the first SOA and one for the other SOAs. The first SOA – with stimulation 150 ms before the onset of the bottle – is a special condition that should not be affected by the side of the visuo-tactile stimulation with respect to the following orientation of the bottle. The other four SOA conditions all have the stimulation delivered after the presentation of the bottle, thus resembling the SOA variations applied in the first experiment.

The analysis for SOA1 yielded significant main effects for visual distractor side ($F(1, 26) = 58.94$, $p < .001$; $M_{left} = 141.5$ px, $M_{right} = 190.2$ px) and, this time, for stimulated finger ($F(1, 26) = 5.31$, $p=.029$; $M_{thumb} = 163.9$ px, $M_{index} = 167.9$ px). Importantly, none of the other effects reached significance (all other *p's* ≥.052).

Considering the ANOVA for SOA2 to SOA5, both, bottle orientation ($F(1, 26) = 19.76$, $p < .001$; $M_{up} = 181.7$ px, $M_{down} = 138.4$ px) and visual distractor side ($F(1, 26) = 160.51$, $p < .001$; $M_{left} = 124.3$ px, $M_{right} = 195.8$ px) significantly influenced the mean gaze position. Bottle orientation and stimulated finger significantly interacted ($F(1, 26) = 5.08$, $p = .033$): specifically, in the upright condition the gaze was on the right side of the bottle, and more to the right when the index finger was stimulated, and, conversely, in the upside down condition the gaze was more to the left side of the bottle, and more so when the index finger was stimulated. Moreover, the three-way interaction of orientation, visual distractor, and finger reached significance ($F(1, 26) = 4.39$, $p = .046$). All other interactions involving the SOA remained significant.

3.2.3. Movement Onset Times

As in the first experiment, the orientation x SOA analysis of movement onset times yielded a significant main effect of SOA ($F(2.26, 58.74) = 221.81$, $p < .001$). Earlier stimulations prompted a faster initiation of the movement ($M_{SOA1} = 286$ ms, $M_{SOA2} = 423$ ms, $M_{SOA3} = 524$ ms, $M_{SOA4} = 551$ ms, $M_{SOA5} = 560$ ms). Furthermore, in this case the interaction between bottle orientation and SOA was significant ($F(2.70,70.26) = 3.81$, $p = .017$). For the later SOAs, participants took longer to initiate the movement in case of upright bottles compared to bottles presented upside down.

4. Discussion

We investigated the anticipative nature of the way in which peripersonal space (PPS) is mapped into the future while planning and initiating object interactions. We expected to detect highly adaptive remappings onto the next event boundary, namely the grasping of an object. Seeing that the object's orientation afforded either an overhand or an underhand grasp, we expected an aCCE dependent on the anticipated grasp as well as gaze behavior targeting the future position of the stimulated finger.

Experiment 1 revealed the aCCE in the significant three-way interaction between bottle orientation, visual distractor side, and stimulated finger: response times were significantly faster in the case of congruent stimulations. Already at 200 ms after visual onset of the bottle, the aCCE was significant such that congruency systematically depended on the bottle's orientation. Gaze positions showed a significant bias towards the future position of the stimulated finger, particularly when no visual distractor was present. In the trials with visual distractor, the salient distractor somewhat overshadowed the influence of the finger vibrations on gaze behavior. In sum, results of Experiment 1 confirm the expected, anticipatory remapping of PPS: task-irrelevant visual distractors at the to-be grasped object systematically influenced the verbal response to a vibrotactile stimulation depending on the anticipated grasp. Moreover, gaze behavior was influenced by the vibrotactile stimulation.

The results of Experiment 2 replicate and extend those of Experiment 1. Again, the aCCE reached significance. Moreover, despite the presence of the visual distractor, gaze positions were significantly biased towards the future position of the stimulated finger. Most likely due to the different SOA variations, the aCCE for the individual SOAs reached significance slightly later than in Experiment 1. In both experiments, strong aCCEs were observed for stimulations at movement onset. In Experiment 1, the aCCE was also significant at SOA1 (200 ms after presentation of the bottle) but it failed to reach significance at SOA3 (200 ms after movement onset). In contrast, in Experiment 2 the aCCE still failed to reach significance at SOA3 (250 ms after presentation of the bottle), but it stayed significant at SOA 5 (200 ms after movement onset). This difference is probably due to different strategies employed by the participants in the two experiments. The probability of a stimulation before movement onset was 33% in Experiment 1 (SOA1), compared to 60% in Experiment 2 (SOA1, SOA2, and SOA3). Hence, early movement planning was encouraged in Experiment 1, while later movement planning seemed to be a viable strategy in Experiment 2 – thus avoiding processing conflicts between the two concurrent tasks. Assuming that the aCCE can only be observed once movement planning is sufficiently advanced, this prioritization can explain the absence of the aCCE for SOA3 in Experiment 2. In contrast, the absence of aCCE for SOA3 in Experiment 1 may indicate that the mind already started to remap PPS towards the anticipated final position and orientation of the bottle (i.e. the subsequent bottle placement).

In Spence, Pavani & Driver (2004), the predictability of which hand would be stimulated was manipulated, producing faster responses when predictability was higher, yet not influencing the magnitude of the CCE. However, no motor task was required and hence no remapping would take place. In our case the temporal predictability of the hand stimulation was manipulated five-fold and again response times were faster when predictability was higher. In addition, though, the CCE magnitude was significantly influenced. This can be explained by the fact that the bottle's orientation was unknown in each trial until it became visible. As a result, PPS had to be dynamically remapped onto the bottle in one of two possible manners upon bottle visualization onset, yielding a dynamic aCCE. The temporal variation of the hand stimulation relative to visualization onset resulted in the aCCE magnitude variation. At earlier points in time, PPS remapping was more uncertain and not fully established, yet. Later, the necessary remapping was certain and fully established. Finally, the slight decline at SOA5 in Experiment 2 and the more pronounced decline at SOA3 in Experiment 1 (which timing-wise corresponds to SOA5 in Experiment 2) implies that a further remapping of PPS onto the next event and critical event boundary commenced, that is, bottle transportation and upright bottle release, respectively. While the data as well as the underlying theory of event-oriented anticipatory behavior support this time course interpretation, future studies are necessary to validate it and to understand the involved processes in further detail.

Besides the dynamic aCCE, both experiments show that eye gaze behavior was biased towards the side of the bottle where the stimulated finger would be placed. The absence of the respective interaction for the first SOA in the second experiment, in which case the stimulation was applied before the onset of the bottle, confirms that the interaction between bottle orientation and stimulated finger is indeed related to the anticipatory planning process. Furthermore, Experiment 2 shows that a visual distractor does not fully overshadow this anticipatory, top-down eye gaze influence.

In conclusion, the results support the notion that our minds are indeed "surfing the future" (Clark, 2016), showing that we map sensory stimulations onto each other via spatial predictive encodings in anticipation of the currently aimed-at next event boundary (Butz, 2016). Our eyes explore this boundary to ensure the application of a proper grasp, while the hand begins to expect the upcoming touch of the object before it takes place – and this happens partially even before starting to move. In other words, our results show that PPS is remapped into the future for invoking and controlling goal-directed manual motor behavior, yielding anticipatory crossmodal interactions as well as eye gaze behavior with respect to a currently intended, future body state. Future work should further investigate the nature of the identified anticipatory spatial remappings and the involved neuro-cognitive processes, including their temporal dynamics, dependencies on perceptual and behavioral uncertainties, as well as their hierarchical and event-oriented structure.

Author contributions: A. Farnè and M.V. Butz developed the study concept. A. Belardinelli, J. Lohmann and M.V. Butz contributed to the study design. A. Belardinelli and J. Lohmann performed the testing and data collection. A. Belardinelli and J. Lohmann performed the data analysis and interpretation under the supervision of M.V. Butz. A. Belardinelli, J. Lohmann and M.V. Butz drafted the manuscript. A.Farnè provided critical revisions. All authors approved the final version of the manuscript.

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Appendix

Here we report the details of the full four-way repeated measures ANOVAs (bottle orientation x visual distractor side x stimulated finger x SOA) carried out on the response times for the two experiments, along with follow-up analyses.

A.1 Verbal Response Times (Experiment 1)

The four-way ANOVA of trials with visual distractor yielded two effects. First, there was a main effect of SOA ($F(2, 24) = 20.02$, $p < .001$). Verbal response times decreased with SOA ($M_{SOA1} = 811$ ms, $M_{SOA2} = 723$ ms, $M_{SOA3} = 669$ ms). Furthermore, the three-way interaction of bottle orientation, visual distractor side, and stimulated finger was found to be pronounced ($F(1,12) = 21.38$, $p = .001$). Responses were faster in the congruent conditions, particularly so in the upright condition and when the index finger was stimulated. This interaction is depicted in the central plots of Fig. 3. None of the other main factors nor any of the other interactions reached significance (all other p's $\geq .075$). To probe the time-course of the aCCE, the analysis was repeated for all SOAs separately. The three-way interaction was found to be significant at the first ($F(1, 12) = 6.69$, $p = .024$) and second ($F(1, 12) = 5.18$, $p = .042$), but not the third SOA ($F(1, 12) = 2.34$, $p = .152$). The magnitude of the congruency effect (in terms of the difference in response times between incongruent and congruent conditions) with respect to the different SOA conditions is shown in Fig. 4.

A separate three-way ANOVA (bottle orientation x stimulated finger x SOA) for the trials without visual distractor yielded only a significant main effect of SOA ($F(1.23, 14.78) = 12.48$, $p = .002$; all other p's $\geq .162$).

A.2 Verbal Response Times (Experiment 2)

The four-way ANOVA produced a significant main effect for SOA ($F(2.26, 58.75) = 76.14$, $p < .001$). Again, response times were larger for earlier stimulation ($M_{SOA1} = 931$ ms, $M_{SOA2} = 864$ ms, $M_{SOA3} = 805$ ms, $M_{SOA4} = 755$ ms, $M_{SOA5} = 721$ ms, all comparisons $p \leq .001$ except the comparison between SOA4 and SOA5, $p = .010$). An overview of verbal and manual response times along with the movement times for the different SOA conditions is shown in Fig. 6. The aCCE, reflected by the three-way interaction between bottle orientation, visual distractor side, and stimulated finger was significant ($F(1,26) = 41.23$, $p < .001$). As in the first experiment, participants responded faster in case of congruent stimulation (same side for the visual distractor and the upcoming placement of the stimulated finger). This pattern was more pronounced when the bottle was presented upright. In contrast to the first experiment, the four-way interaction including SOA was significant as well ($F(4,104) = 3.23$, $p = .015$; all other p's $\geq .056$). To follow up on the four-way interaction we conducted three-way ANOVA analyses for each of the SOAs (see Fig. 7 for an overview of the aCCEs across SOA conditions).

Stimulation at hand movement onset (SOA4) showed a clear aCCE ($F(1,26) = 26.42$, $p < .001$). The same effect was found for the stimulation during the hand movement (SOA5): $F(1,26) = 12.77$, $p = .001$. For earlier SOAs, the three-way interaction did not reach significance (all other *p's* $\geq .111$).