Title

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Unflinching Predictions: Anticipatory Crossmodal Interactions are Unaffected by the Current Hand Posture

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Abstract

According to theories of anticipatory behavior control, action planning and control is realized by activating desired goal states. From an event-predictive perspective, this activation should focus sensorimotor processing on expected, upcoming event boundaries. Previous studies have shown that peripersonal hand space (PPHS) is remapped to the future hand location in a grasping task before the movement commences. Here, we investigated if the current hand posture interferes with the anticipatory remapping of PPHS. Participants had to grasp virtual bottles from two differently oriented starting postures. During the prehension, they received a vibrotactile stimulus on their right index finger or on their thumb, while a visual stimulus appeared at the bottle, either matching the future finger position, or not. Participants had to name the stimulated finger. While the hand posture affected verbal response times, the anticipatory remapping remained unchanged. Apparently, the predictive processes that realize the anticipatory remapping, generalize over initial hand postures.

Keywords: Event Predictive Cognition; Anticipatory Behavioral Control; Peripersonal Space; Virtual Reality

Introduction

According to theories of anticipatory behavior control, the initiation of goal-directed actions requires the activation of event-predictive structures or *schemata* (EPSs; e.g. Butz, 2016; Butz & Kutter, 2017; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Hoffmann, 2003; Zacks, Speer, Swallow, Braver, & Reynolds, 2007; Richmond & Zacks, 2017). These EPSs are considered to encode the final outcome of an action, but also the sensorimotor changes that usually unfold during an action, as well as the situational pre-conditions of successful action execution. In relation to free-energy based theories of cognition (Friston, 2009), EPSs are assumed to be involved in the more general active inference process that realizes action planning, decision making, and control (Butz, 2016). This perspective is closely related to the *ideomotor principle* (Greenwald, 1970) from cognitive psychology and essentially states that anticipated final outcomes and sensorimotor dynamics are activated before actual goal-directed motion takes place.

Empirical evidence for the assumed active inference process comes from eye-tracking studies, showing that the fixation pattern on a grasping target depends on the interaction goal (Belardinelli, Stepper, & Butz, 2016). Apparently, visual processing was tuned to those spatial locations which were critical for a successful object interaction. Considering the multisensory information, which is expected to be represented in EPSs, predictive processing should not be limited to eye-movements, but should also involve other action relevant representations. One example fur such representations are spatial body representations, like the peripersonal hand space (PPHS). PPHS seems crucial for successful object interactions and tool-use (Graziano & Cooke, 2006) . PPHS has also been found to be highly flexible in adapting to interaction possibilities (Holmes, 2012). Furthermore, PPHS enforces multisensory processing (Holmes & Spence, 2004; Bernasconi et al., 2018). According to the outlined theory, one would expect that PPHS is involved in predictive processing and might be remapped towards the grasping target during action planning. If this is the case, typical PPHS-related effects should be observed at the grasping target before the actual hand arrives. One typical indicator of PPHS is the selective interaction between vision and touch, which can be assessed by means of the crossmodal congruency paradigm (Spence, Pavani, Maravita, & Holmes, 2004).

In crossmodal congruency tasks, participants have to indicate the position of a tactile stimulation. Task-irrelevant visual stimuli occurring close to the stimulated body part can interfere with tactile perception. For instance, participants are slower to identify whether thumb or index finger received a tactile stimulation, if a LED is flashed at the non-stimulated finger (incongruent), whereas a flash at the location of the stimulated finger prompts a faster response (congruent). Previous studies indeed showed that interference between vision and touch can occur in object interaction tasks at the target object location even before movement initiation (Brozzoli, Pavani, Urquizar, Cardinali, & Farnè, 2009; Brozzoli, Cardinali, Pavani, & Farnè, 2010). This implies an anticipatory crossmodal congruency effect (aCCE), which can be used to investigate the anticipatory remapping of PPHS. In more recent studies (Belardinelli, Lohmann, Farnè, & Butz, 2018; Lohmann, Belardinelli, & Butz, 2019; Patané et al., 2018), it was shown that the aCCE can be observed on a trialwise basis without explicit instruction of a certain grasping type. These results imply that the aCCE indeed reflects an adaptive remapping due to action planning instead of a general shift in spatial attention. Apparently, PPHS is involved in the guidance of goal-directed actions, by providing a mapping between the space that can be interacted with and the according actions (Bufacchi & Iannetti, 2018).

While these results imply that PPHS is engaged in predictive processing, some aspects of this mechanism remain illusive. For instance in the studies of Belardinelli et al. (2018) and Lohmann et al. (2019), the orientation of the final grasp modulated the strength of the aCCE. In case of underhand grasps, the aCCE was smaller compared to overhand grasps. This might be due to the fact that underhand grasps are less frequent in object interactions, rendering the planning more difficult. However, since the initial hand posture in these experiments was closer to the overhand grasp, this effect could also imply that the assumed prediction process does not completely generalize over the initial hand posture. This would dovetail with previous results from research on motor imagery, especially on mental rotation, which showed a strong interaction between ongoing motor planning and the actual posture (Parsons, 1987; Qu, Wang, Zhong, & Ye, 2018). Hence, our main aim in the present study was to investigate whether the aCCE depends on a postural match between initial and future hand position. If the aCCE would be affected by variations in the initial posture, this would imply that the sensorimotor changes assumed to be encoded in EPSs are less general than expected. If not, this would corroborate further evidence for the assumption that the aCCE is indeed an indicator for a general movement planning mechanism.

We conducted a behavioral study to discern these alternatives. Participants performed a grasp-and-carry task in VR, interacting with a virtual bottle. At different times before and during the interaction, participants received a tactile stimulation at the thumb or index finger. Concurrently, a visual stimulus appeared at the left or right side of the bottle, either matching the future location of the stimulated finger, or not. Participants had to respond as fast as possible, by verbally naming the finger that was stimulated. A typical aCCE would be reflected by faster responses if the visual stimulus matched the future finger position. The starting position of the hand varied from trial to trial, participants had either to start from a more clockwise, or more counterclockwise rotated starting posture. The main question was whether aCCEs would be modulated by this trialwise variation of the hand orientation.

Method

Participants

Twenty-four students from the University of Tübingen participated in the experiment (ten females). Their age ranged from 19 to 26 years (M = 21.2, SD = 1.9). All but one participant were right-handed and all participants had normal or corrected-to-normal vision. Participants provided informed consent and received either course credit or a monetary compensation for their participation. Two participants had difficulties with the virtual grasping procedure and could not complete the experiment. The respective data were not considered in the analysis.

Apparatus

Participants were equipped with an Oculus Rift© DK2 stereoscopic head-mounted display (Oculus VR LLC, Menlo Park, California). Motion tracking of hand movements was realized with a Leap Motion© near-infrared sensor (Leap Motion Inc, San Francisco, California, SDK version 3.2.1). The Leap Motion© sensor provides positional information regarding the palm, wrist, and phalanges. This data can be used to render a hand model in VR. Participants responded verbally to the tactile stimulation. In order to so, participants were equipped with a headset. Speech recognition was implemented by means of the Microsoft Speech API 5.4. The whole experiment was implemented with the Unity® engine 2017.4.5f1 using the C# interface provided by the API. During the experiment, the scene was rendered in parallel on the Oculus Rift and a computer screen, such that the experimenter could observe and assist the participants.

Tactile stimulation was realized by means of two small (10 mm $\times$ 3.4 mm) shaftless vibration motors attached to the tip of the thumb and the index finger of the participants. The motors were controlled via an Arduino Uno microcontroller (Arduino S.R.L., Scarmagno, Italy) running custom C software. The microcontroller was connected to the computer via an USB port, which could be accessed by the Unity® program. The wiring diagram as well as additional information regarding the components can be found at the first author's webpage. [1]

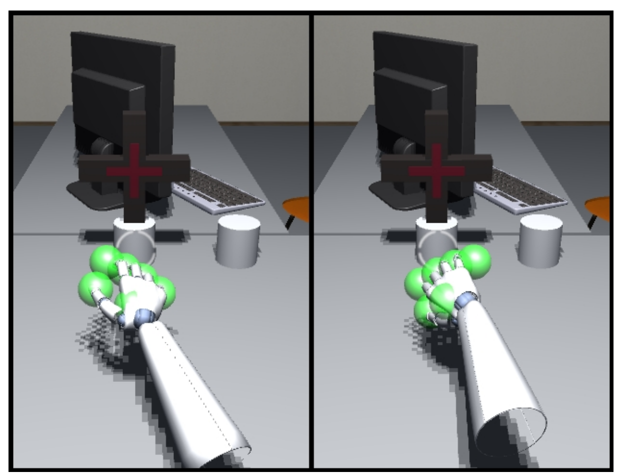

Figure 1: The VR scene with the clockwise oriented (left panel) and the counterclockwise oriented (right panel) starting postures. Participants had to grasp a bottle which appeared on the central pedestal and place it upright onto the right pedestal. The bottle could be either upright, or rotated.

Virtual Reality Setup

The VR setup put participants in an office-like room. Centered about 50 cm in front of them, a pedestal was placed, where, during the trials, the target object appeared. The target was always a 3D model of a plastic bottle either oriented upright or upside down. The bottle was 15 cm in height, sub-

[1] https://uni-tuebingen.de/de/26084

tending a visual angle of 17.1° at the initial location. A second pedestal, 15 cm to the right of the first one, served as the target location (see Fig. 1). The positions of the pedestals were marked with actual cardboard boxes providing haptic feedback regarding the bounds of the task space (participants were seated in a way that they had to stretch their arm to reach the pedestals). Instructions and feedback were presented in different text-fields, aligned at eye-height. At the beginning of a trial, a fixation cross appeared at the initial location of the target bottle (see Fig. 1). The fixation cross was 10 cm wide and 10 cm high, subtending a visual angle of 11.4°. The visual distractor was realized by means of a red, spherical flash with a diameter of 8 cm (equal to a visual angle of 8°) appearing at the left or right side of the bottle.

Procedure

At the beginning of the experiment, participants received a verbal instruction regarding the VR equipment. Then they were equipped with vibration motors and familiarized with the tactile stimulation. Participants were then seated comfortably on an arm chair and put on the HMD. Before the actual experiment, participants performed a grasping training and trained the verbal response until they felt comfortable with both tasks. In the grasp training, participants performed the grasp-and-carry task without receiving a tactile stimulation. Furthermore, participants could familiarize themselves with the two different starting positions. In the verbal response training, participants did not perform a grasping movement, but remained with their hand in the starting position.

The actual experiment combined both tasks in a dual-task paradigm. At the beginning of each trial, participants had to move their right hand into a designated starting position, consisting of red, transparent spheres indicating the required positions of the fingers and the palm. There were two possible variations of the starting position. One was tilted by 15° clockwise in the frontal plane, and one was tilted by 15° counterclockwise in the frontal plane. Accordingly, this required participants' to rotate their hands either clockwise or counterclockwise. The spheres turned green when the respective fingers were in position (see Fig. 1). Furthermore, participants had to maintain a stable looking direction on a fixation cross. Once both requirements were met for 1000 ms, the fixation cross as well as the visible markers of the initial position disappeared and a bottle appeared on the central pedestal. The bottle was either oriented upright, or upside down. Participants were instructed to grasp the bottle with a power grasp, and put it in an upright orientation within the target location. We did not explicitly instruct a underhand grasp in case of upside down bottles, however, all participants performed this kind of grasp. The initial hand postures were close to the respective grasping hand posture for the upright oriented bottle (clockwise hand posture), or the upside down bottle (counterclockwise hand posture).

Besides the grasp-and-carry task, participants had to discriminate which finger received a vibrotactile stimulation and to report the stimulated finger as fast as possible (by saying "index or "thumb, i.e., in German "Zeigefinger or "Daumen) upon vibration detection. The onset of the tactile stimulation varied from trial to trial. A visual distractor appeared at the same time at either the right or the left side of the bottle. Depending on the bottle orientation, this was expected to yield different congruent and incongruent conditions with respect to the aCCE (see Fig. 2).

The experiment consisted of 480 trials, presented in a single block. The experiment was self-paced and participants could pause between trials. The whole procedure took between 90 and 120 minutes, including preparation and training.

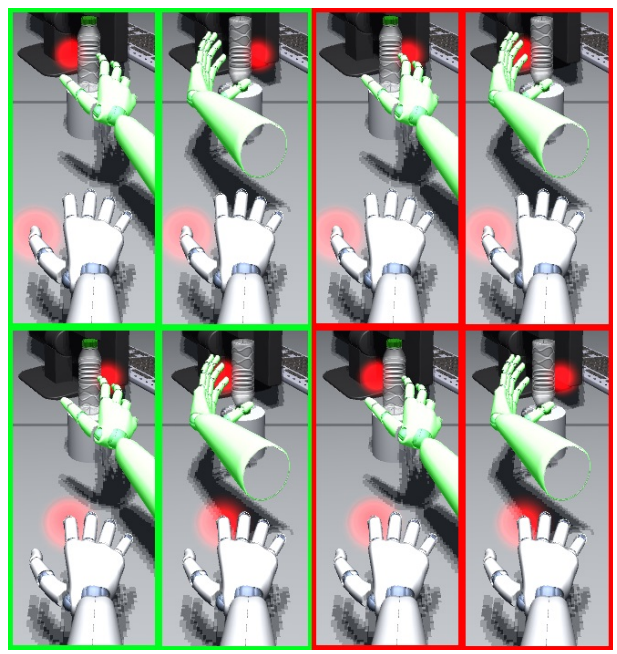

Figure 2: The different congruency conditions with respect to the future hand position (transparent green hand), depending on bottle orientation. The stimulated finger is indicated by a red flash, this was done for the sake of visibility, the participants received no visual cue regarding the tactile stimulation. Red frames indicate incongruent conditions, congruent conditions are marked with a green frame. Please note that the initial hand posture was different from the one shown in this image (cf. Fig 1), the flat hand posture here was used for the sake of visibility.

Factors, Measures, Data Treatment

We varied five factors across trials. First, the target bottle could be oriented upright or upside down (*orientation*). Second, the visual distractor could appear either on the left or the right side of the bottle (*distractor*). Third, the tactile stimulation could be applied either to the thumb or to the index finger (*stimulation*). Fourth, we varied the initial hand posture - clockwise or counterclockwise - which participants had to maintain to start the trial (*posture*). Fifth, we varied the onset of the tactile stimulation and the visual distractor (*SOA*): 250 ms after presentation of the bottle (SOA1), at movement onset (SOA2), or after the hand traveled half-way to the bottle (SOA3). We repeated the 2 (distractor) $\times$ 2 (stimulation) $\times$ 2 (orientation) $\times$ 2 (posture) $\times$ 3 (SOA) factor combinations ten times, yielding 480 trials. The primary dependent measure were the verbal response times for naming the stimulated finger. Data from error trials (wrong or no verbal response, 1.8% of the trials) were excluded from the response time analyses. Furthermore, we analyzed the error data using a mixed effects logistic regression.

Congruency

For our hypothesis, possible aCCE's were most relevant. aCCE's are reflected by three-way interactions between the factors orientation, distractor, and stimulation (cf. Fig. 2) . For instance, in the case of an upright bottle a tactile stimulation of the index finger along with a visual distractor on the right side of the bottle is congruent. To focus the analysis, we recoded the data accordingly and obtained a congruency factor, combining the visual distractor and tactile stimulus factor. For the response times, we report an analysis of the respective differences (incongruent - congruent) with a 2 (orientation) $\times$ 2 (posture) $\times$ 3 (SOA) ANOVA. In this analysis a significant, positive intercept would indicate a significant aCCE (faster responses in congruent as opposed to incongruent conditions).

Results

Verbal response times from the 22 considered participants were analyzed with a 2 (congruency) $\times$ 2 (orientation) $\times$ 2 (posture) $\times$ 3 (SOA) repeated measures ANOVA. Verbal response times differences between incongruent and congruent conditions were further analyzed with a 2 (orientation) $\times$ 2 (posture) $\times$ 3 (SOA) repeated measures ANOVA. Only correct trials were included in the RT analysis. All reported post-hoc comparisons were submitted to a Holm-Bonferroni correction. The analyses were carried out with R (R Core Team, 2016) and the `ez` package (Lawrence, 2015). In case of violations of the assumption of sphericity, p-values were submitted to a Greenhouse-Geisser adjustment. Error rates were analyzed with mixed effects logistic regression, using the `lme4` package (Bates, Mächler, Bolker, & Walker, 2015).

Verbal Response Times

The 2 (congruency) $\times$ 2 (orientation) $\times$ 2 (posture) $\times$ 3 (SOA) repeated measures ANOVA yielded significant main effects for orientation ($F(1,21) = 7.63$, $p = .012$, $\eta_p^2 = .27$), congruency ($F(1,21) = 32.57$, $p < .001$, $\eta_p^2 = .61$), and SOA ($F(1,21) = 28.04$, $p < .001$, $\eta_p^2 = .57$), as well as significant interactions between orientation and SOA ($F(2,42) = 8.74$, $p = .001$, $\eta_p^2 = .29$), orientation and posture ($F(1,21) = 5.54$, $p = .028$, $\eta_p^2 = .21$), orientation and congruency ($F(1,21) = 9.55$, $p = .006$, $\eta_p^2 = .31$), SOA and congruency ($F(2,42) = 10.39$, $p = .001$, $\eta_p^2 = .33$), as well as a three-way interaction for orientation, congruency, and SOA ($F(2,42) = 7.32$, $p = .002$, $\eta_p^2 = .26$; all remaining p's $\geq .168$).

Participants responded faster to upright bottles ($M_{upright}$ = 700 ms vs. $M_{rotated}$ = 713 ms), and in case of congruent stimulation ($M_{congruent}$ = 691 ms vs. $M_{incongruent}$ = 722 ms). Verbal RTs decreased with SOA (M_{SOA1} = 742 ms, M_{SOA2} = 710 ms, M_{SOA3} = 669 ms; all respective p's $<.001$). Regarding the interaction between orientation and SOA, participants responded faster to bottles oriented upright at SOA1 ($t(21) = 3.21$, $p = .016$) and SOA2 ($t(21) = 4.02$, $p = .004$), for SOA3, this difference was no longer significant ($t(21) = -0.54$, $p = .595$). Post-hoc analyses of the orientation $\times$ posture interaction showed that participants responded faster to upright than to upside down bottles when starting in a clockwise posture ($t(21) = 3.59$, $p = .010$). The respective difference was not significant for the counterclockwise posture. Furthermore, response times in case of upright bottles and a clockwise posture were significantly faster than response times in the other three conditions (all respective p's $<.04$).

To further analyze the interactions involving the congruency factor, we analyzed the RT differences between incongruent and congruent conditions with a 2 (orientation) $\times$ 2 (posture) $\times$ 3 (SOA) ANOVA. The analysis yielded a significant intercept ($F(1,21) = 47.00$, $p < .001$, $\eta_p^2 = .69$), significant main effects of SOA ($F(2,42) = 20.43$, $p < .001$, $\eta_p^2 = .49$) and orientation ($F(1,21) = 16.43$, $p = .001$, $\eta_p^2 = .44$), as well as a significant interaction between orientation and SOA ($F(2,42) = 9.20$, $p = .002$, $\eta_p^2 = .30$). No further main effects or interactions reached significance (remaining p's $\geq .230$).

The congruency effect was significantly larger at SOA3 compared to SOA1 and SOA2 (ΔM_{SOA1} = 17 ms, ΔM_{SOA2} = 20 ms, ΔM_{SOA3} = 60 ms; all respective p's $<.001$). For bottles presented upright, the congruency effect was larger than for upside down bottles ($\Delta M_{upright}$ = 54 ms vs. $\Delta M_{rotated}$ = 11 ms). Regarding the interaction between orientation and SOA, after adjusting for multiple comparisons, the only significant difference between upright and upside down bottles was found at SOA3 ($\Delta M_{upright}$ = 98 ms vs. $\Delta M_{rotated}$ = 23 ms; $t(21) = 4.60$, $p < .001$).

To further probe the significance of the aCCE, all of the 2 (orientation) $\times$2 (posture) $\times$ 3 (SOA) mean differences were tested against a true mean of 0. The results are shown in Fig. 3.

Error Rates

Both error and correct trials of all participants, except the trials without response (65 out of 10560 trials) were coded as 0 (error) or 1 (correct) and entered into a mixed effects logistic regression analysis with a binomial distribution. We compared models of increasing complexity with likelihood ratio tests to determine whether the factors orientation, posture, congruency, and SOA were required to account for the error pattern. We kept the error structure simple, applying only a random intercept per participant. After the identification of the null model, we added fixed effects for the ex-

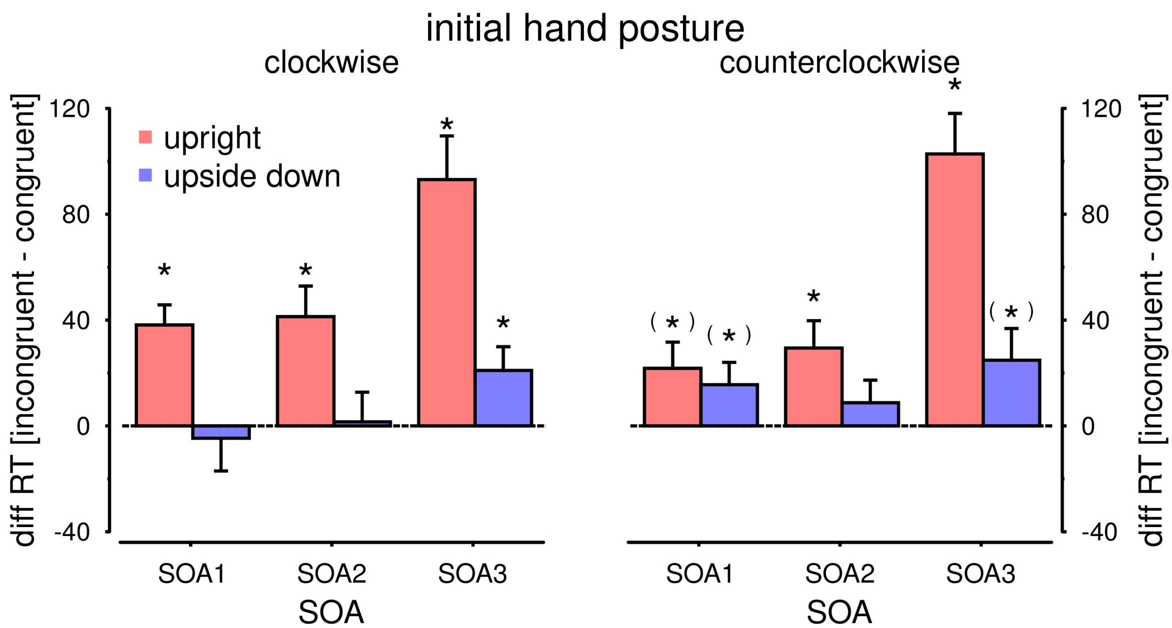

Figure 3: The aCCE – measured as the response time difference between congruent and incongruent trials – including its temporal dynamics and dependency on bottle orientation and initial hand posture. Significant differences from 0 are indicated with an asterisk. Asterisks in brackets indicate comparisons which failed significance after adjusting for multiple comparisons. Error bars indicate the standard error of the mean.

perimental factors to the model as long as the likelihood ratio test between the simpler and the more complex model yielded significant results (with α = .05). We only compared nested models differing with respect to one factor. Models with a single fixed effect were compared with the null model, models with two fixed effects were compared with models with one fixed effect and so on. The best fitting model involved fixed effects for the factors SOA, orientation and congruency, as well as the interaction between congruency and orientation (see Tab. 1, only significant effects are included)[2]. The error risk is increased by a factor of 3.4 in case of later SOAs compared to earlier ones. The error risk decreases by a factor of 0.28 in case of rotated compared to upright bottles. This pattern is further modified by the interaction between congruency and orientation. For upright bottles, the error risk increases in case of incongruent stimulation by a factor of 8.5, for upside down bottles, there is no difference in the error risk for congruent and incongruent stimulation.

Table 1: Effect estimates for the best fitting binomial mixed effects logistic regression model regarding the error rates ($\mathrm{df} = 7, \mathrm{logLik} = -803.3, \mathrm{BIC} = 1671.4$). The logit estimates have been transformed to odds, only significant effects (α = .05) are shown. Z statistics for the Wald test and according p-values are presented in the last two columns.

fixed effect	**odds**	**95% CI**	**Z**	**p**
intercept	0.005	[0.002 , 0.009]	-15.91	$<.001$
SOA3	3.364	[2.295, 4.930]	6.22	$<.001$
orientation	0.288	[0.155, 0.534]	-3.95	$<.001$
orientation $\times$ congruency	8.540	[4.150, 17.574]	5.83	$<.001$

Discussion

We aimed at investigating the mechanism of anticipatory remapping of PPHS in advance of a prehension movement. In order to do so, we investigated anticipatory cross-modal congruency effects (aCCEs) during virtual grasping movements. Participants had to grasp virtual bottles with their right hand, while receiving a tactile stimulation on thumb or index finger of that hand along with a visual stimulation close to one of the future finger positions. The visual distractor could either match the future finger location or not. In line with earlier findings (Belardinelli et al., 2018; Brozzoli et al., 2009, 2010; Lohmann et al., 2019; Patané et al., 2018), we observed dynamic aCCEs, which were more pronounced at later SOAs. To probe whether the strength of the aCCE depends on the match between current and future hand posture, we varied the starting posture of the participants' hands from trial to trial. Participants started either with a clockwise (matching the grasp for an upright bottle), or counterclockwise (matching the grasp for a upside down bottle) posture. While we observed response time differences for the clockwise posture (faster responses for upright bottles, delayed responses for upside down bottles), the congruency effect itself remained unaffected by the initial hand posture. Also with respect to the

[2]Please note that the model assuming the three-way interaction between all factors provided a slightly better fit, however, the respective BIC was much larger than the one of the selected model.

error rates, the initial hand posture yielded no significant influence. A closer inspection of the response time differences for incongruent compared to congruent stimulation implied a small increase in the congruency effect for upside down bottles in case of the counterclockwise posture, while at the same time slightly decreasing the congruency effect for upright bottles. However, these effects seem too small to become significant with the applied sample size. In general, congruency effects were more pronounced for upright compared to upside down bottles (with respect to both RTs and errors). Since this was still the case for the counterclockwise posture, this difference seems not to be due to an initial mismatch between current and future hand position. It rather implies a planning advantage for canonical object orientations.

While the observed interaction between bottle orientation and hand posture dovetails with findings that the current body posture can indeed interfere with mental imagery processes (Parsons, 1987; Qu et al., 2018) and has a significant weighted impact on the actual chose hand grasp posture (Herbort & Butz, 2012), this modulation did not apply to the congruency effect itself. Apparently, the anticipatory control process that gives rise to the aCCE generalizes over the actual hand posture, remapping PPHS towards the future goal, irrespective of the current hand posture. In general, the reported results on the aCCE provide support for theories of probabilistic, event-oriented, active inference (Butz, 2016; Butz & Kutter, 2017): the results confirm that PPHS is adaptively remapped onto future event boundaries during the preparation and for the control of goal-directed behavior.

However, the understanding of the remapping mechanism requires further investigation. In our data, as well as in the results reported by Belardinelli et al. (2018), and Lohmann et al. (2019), the aCCE was much more pronounced for bottles presented upright. It seems that the remapping works more efficient in case of canonical object orientations. As it was pointed out by Bufacchi and Iannetti (2018), measures of PPHS like the aCCE are not only modulated by proximity, but by many other factors like learning, stimulus valence, and environmental characteristics. Hence, a modulation of the aCCE by familiarity seems plausible, but a systematic comparison between bottles and objects with a less pronounced canonical orientation is pending. Moreover, there is still much further light to be shed on the dynamics of this process and its dependency on event-predictive precision estimates. From the event-predictive, anticipatory behavioral control perspective, it can be expected that the future horizon will reach the deeper into the future, the more precise the predictive model estimates are expected to be. That is, the higher our confidence about the upcoming environmental events and sequences thereof, the more we will look ahead and act in a more versatile and flexible goal-directed manner.

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