The crossed-hands deficit in temporal order judgments occurs for present, future, and past hand postures

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The crossed-hands deficit in temporal order judgments occurs for present, future, and past hand postures*

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Abstract—**When people judge the temporal order (TOJ task) of two tactile stimuli at the two hands while their hands are crossed, performance is much worse than with uncrossed hands [1]. This crossed-hands deficit is widely considered to indicate interferences of external spatial coordinates with body-centered coordinates in the localization of touch [2]. Similar deficits have also been observed when people are only about to move their hands towards a crossed position [3-5], suggesting a predictive update of external spatial coordinates. Here, we extend the investigation of the dynamics of external coordinates during hand movement. Participants performed a TOJ task while they executed an uncrossing or a crossing movement, and during presentation of the TOJ stimuli the present posture of the hands was crossed, uncrossed or in-between. Present, future and past crossed-hands postures decreased performance in the TOJ task, suggesting that the update of external spatial coordinates of touch includes both predictive processes and processes that preserve the recent past. In addition, our data corroborate the flip model of crossed-hands deficits [1], and suggest that more pronounced deficits come along with higher time requirements to resolve interferences.**

I. INTRODUCTION

Every day we are touched numerous times on the skin−be it by other humans, leaves falling down or by incidentally contacting objects during our own movements. In order to localize the origin of touch in external space somatosensory information about the touched location at the body needs to be combined with proprioceptive and visual information about body posture [2]. External spatial coordinates of tactile events seem to be automatically updated, as indicated by the crossed-hands deficit in TOJ tasks: A crossed-hands posture deteriorates the judgment which of the two hands was stimulated first, suggesting that external spatial coordinates interfere with body-centered ones. Here, we investigate the dynamics of updating external coordinates during hand movement, by studying how present, future and past crossed-hands postures interfere with temporal order judgments.

The crossed-hands deficit has been initially reported in [1]. Participants were presented with two tactile stimuli that were applied in brief succession to the two ring fingers. Stimulus onset asynchronies (SOAs) ranged from ±5 to ±1500ms. With uncrossed hands participants were well able to correctly judge the temporal order for SOAs as short as 70ms. With crossed hands, however, participants required much larger SOAs to achieve similar performance and judgments were inverted for SOAs around 100-200ms. The crossed-hands deficit turned out to be stable and persistent, across stimulus types, response modes, limbs, gender or extended practice [1, 6-10].

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In principle the TOJ task ("Which hand was stimulated first?") in the crossed-hands experiments could be solved using body-centered information alone [2]. In [1] the deficit was hence explained by the assumption that tactile events of the TOJ task are automatically coded in external spatial coordinates. As a consequence when the hands are crossed remapping to body coordinates is required, which takes time. With short SOAs < 300 ms it can happen that remapping is not completed before the second stimulus is perceived, resulting in an inverted flip. Later, the same authors suggested that integrating the tactile signals into an apparent motion plays a key role in this process [11, 12]. In contrast, in [6, 10] it is assumed that the tactile stimuli are first coded in body-centered and then remapped in external coordinates. Errors in crossed-hands conditions are explained by confusion between external and body-centered coordinates, and resolving takes time. According to a similar approach in [13], external and body-centered coordinates are integrated with weights that depend on the task, yielding errors in crossed-hands conditions. Thus, all four approaches agree that the crossed-hands deficit results from discrepancies between body-centered and external spatial coordinates, while non-spatial explanations for the crossed-hands deficit have been discounted [2].

In [3, 5] the crossed-hands deficit was used to study the dynamics of updating external spatial coordinates during movement. In the experiment, vibrotactile stimuli were applied to the two hands (SOAs: -100ms or +100ms) closely before participants started bimanual movements. The hands were moved along the body midline from an uncrossed to a crossed posture, from crossed to uncrossed or straight ahead. Error rates in a TOJ task were low in the straight condition. In the crossed-to-uncrossed condition error rates were higher for early TOJ stimuli, and decreased for stimulus presentation at time points closer to movement start. For the uncrossed-to-crossed condition it was the other way round. These results show that future hand positions affect TOJs and indicate a predictive update of external spatial coordinates before movement. In [4] TOJs were studied before during and after bimanual movement (SOAs: ±50ms ±110ms), and for four conditions, uncrossed-to-uncrossed, uncrossed-to-crossed, crossed-to-uncrossed, crossed-to-crossed. Both before and during movement crossed-hands postures at movement start as well as at movement end decreased TOJ performance, whereas after the movement only hand posture at movement end played a role. The results in [4] demonstrate that before movement both future and present hand coordinates influence touch localization, whereas after movement only present hand coordinates play a role, but not past ones. It is less clear how touch localization during movement is influenced by future, present and past hand coordinates, because in this condition the present hand position (crossed or uncrossed) during presentation of TOJ stimuli was undefined and might even have varied between trials.

Here, we studied the dynamics of touch localization during movement by dissociating the influences of future, past, and present hand postures. Participants performed a TOJ task while they executed an uncrossing or a crossing movement. During presentation of the two TOJ stimuli the hands were crossed, uncrossed or in-between. By this design present crossed and uncrossed postures were combined with future or past crossed postures. The TOJ task included a wide range of SOAs (± 10, ±20, ±40, ±80, ±140 and ±200ms). As a rough measure of TOJ performance, we analyzed, similar to [4], an estimate of just noticeable differences (JNDs) in the TOJ task; a more detailed analyses of the involved processes was based on a "flip model" [1]. The flip model describes individual TOJ performance in the crossed-hands condition by a baseline performance in uncrossed conditions, and the probability to invert the baseline judgment (e.g. from right-first to left-first) as a function of SOA. The probability function for flips is Gaussian-shaped and characterized by its standard deviation (~time window of flip) and peak amplitudes of flip probability. Higher peak flip amplitudes indicate a larger number of reversed temporal order judgments; the time window of flip indicates up to which SOA the judged temporal order of the two stimuli is considerably confused. Individual data in [1] were well fit by the flip model. Individual time windows were around 300ms, peak amplitudes considerably differed between individuals.

II. Methods

A. Participants

The experiment took about 9 hours. We were able to collect data from 9 healthy students from Giessen University (21 -27 years of age, average 23 years, all females, 7 right-handed), which participated for pay (8€/hour). They were naïve to the purpose of the study. One participant did not show the crossed-hands deficit in stationary control conditions (JNDs 84 & 88 ms in uncrossed and crossed conditions, respectively), and was hence not included in the analyses.

B. Setup and Stimuli

Participants sat at a visuo-haptic workbench (Fig. 1, left) including a PHANToM 1.5A force feedback device (resolution 0.03 mm, 1000 Hz; 38 x 27 x 20 cm^3 workspace), a 22" LCD screen (Samsung, 120 Hz), wireless stereo glasses (Nvidia 3D Vision kit), two tactile actuators (Haptuator Mark II, Tactile Labs) and headphones (Sony MDR-XD100). The two tactile actuators were embedded in thimble-like holders, in which participants inserted the distal phalanx of their left and right index fingers. One of the finger holders was connected to the force-feedback device, the other was fixed on the table, just below the center of the workspace. The computer monitor was viewed through a mirror via the stereo glasses (40-cm viewing distance; head stabilized by chinrest). The mirror occluded vision from the participant's hands. The visual display served to guide participants through the experiment, e.g. by showing the movements' start positions in 3D-space. All devices were connected to a PC which controlled the experiment, collected responses and recorded finger positions from the force feedback device.

During the experiment, one index finger was held stationary, the other index finger moved periodically back and forth along the x-axis. In line with previous literature [14] we call each unidirectional movement segment a "stroke". Participants produced left-to-right and right-to-left strokes, and in the last stroke one vibrotactile stimulus (sine-wave 50Hz, 10 ms duration) was presented to each index finger. Auditory metronome signals (sine-wave 698 Hz, 20 ms duration) were presented once a second to set the pace for the moving index finger. Additional auditory feedback signals (sine-wave 500 Hz, 20 ms duration) were used to inform participants about turning points, i.e. where to stop movement and reverse movement direction. White noise masked the sounds of the actuators and of the force feedback device. The force feedback device confined finger movements by a virtual corridor of 5 mm depth (z-axis) and 350 mm length (x-axis). The movement corridor was 40 mm above (y-axis) the stationary finger.

C. Design

In a typical trial, participants performed three horizontal strokes with one index finger, and during the third stroke two vibrotactile stimuli were presented to the moving and the stationary index finger, respectively. The task was to judge which of the two vibrotactile stimuli was presented first (temporal order judgment task, TOJ). We manipulated the

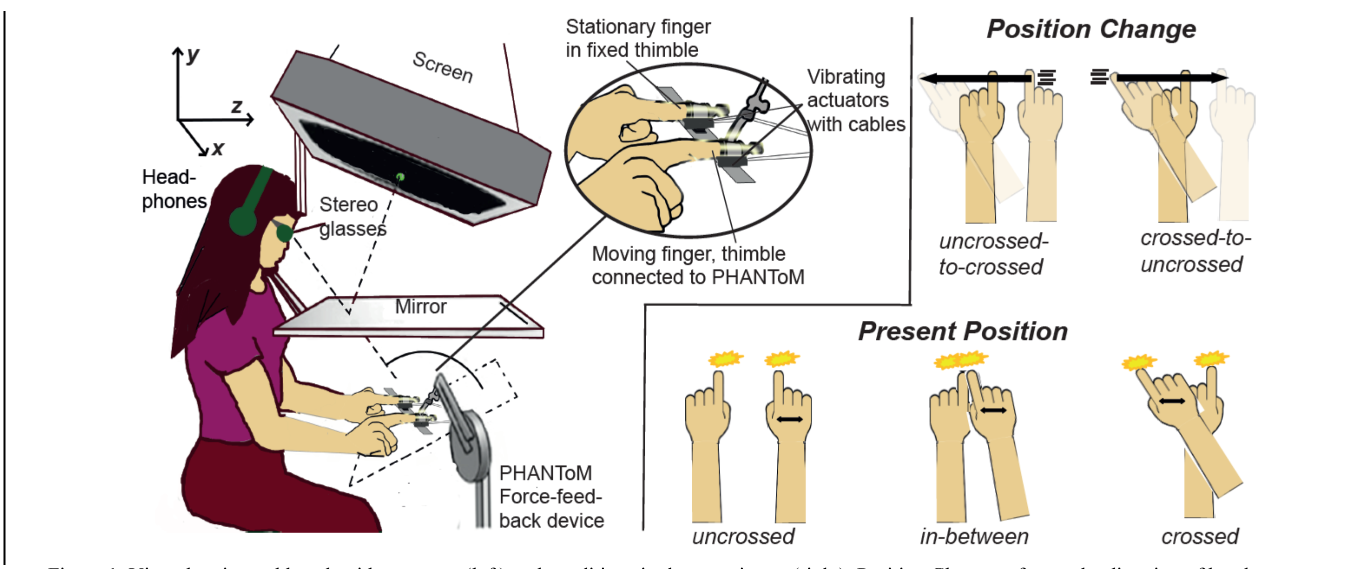

Figure 1. Visuo-haptic workbench with actuators (left) and conditions in the experiment (right). Position Change refers to the direction of hand movement (indicated by black arrow) in that stroke during that vibrotactile stimuli are delivered; Present Position refers to the relative position of the two index fingers during the period of stimulus delivery (indicated by yellow flashes).

Present Position of the hands during the time period when the two vibrotactile stimuli were delivered (crossed vs uncrossed vs in-between; Fig. 1, right) and the Position Change during the third stroke (crossed-to-uncrossed vs. uncrossed-to-crossed). In addition to the movement conditions we implemented stationary control conditions (crossed, uncrossed, in-between); for sake of consistency in the stationary control condition the finger connected to the PHANToM is still referred to as "moving finger". In each condition in half of the trials, the left index finger was the moving finger and the right index finger the stationary one, in the other half it was vice versa. In the uncrossed-to-crossed (movement) conditions the initial stroke, and thus also the third stroke, started on the moving finger's side (left side for left finger and vice versa), so that in this stroke the hands were first uncrossed and later crossed. In the crossed-to-uncrossed conditions the initial and third strokes started on the opposite side. In the stationary control conditions, the "moving finger" was fixed by forces from the force-feedback device in one of three positions.

The vibrotactile standard stimulus was delivered to the moving finger either when it was above the stationary finger (0 mm), 70mm offset towards the moving finger's side or 70mm offset towards the opposite side, realizing the in-between, uncrossed and crossed Present Positions of the hand, respectively. In the respective conditions index fingers were either uncrossed or crossed during the onsets of both vibrotactile stimuli as computed from Eq. 1 (except for most extreme SOAs 200 and -200ms). The vibrotactile comparison stimulus was delivered to the stationary index finger with SOAs of ± 10 ms, ± 20 ms, ± 40 ms, ± 80 ms, ± 140 ms or ± 200 ms with respect to the standard stimulus (negative sign indicating that the comparison stimulus was presented first). Using the method of constant stimuli we determined relative frequencies of the response that the stationary finger was stimulated first as a function of SOA, and derived model parameter from these psychometric functions (data analyses).

D. *Procedure*

Each trial in the movement conditions started with a voice saying "left" or "right" and a visual landmark, which both indicate the starting position of the moving finger (140 mm left or right to center). Once the participants reached the starting position, metronome signals and white noise started. Participants were instructed to wait for two metronome signals and afterwards to move forth and back along the x-axis in synchrony with the metronome; auditory feedback signals were given when the moving finger reached turning points for the movement (140 mm left or right to center). The screen went black during finger movement. In the third stroke the vibrotactile stimuli were presented to stationary and moving finger. Participants responded by moving the moving finger to the extreme right and then up to respond that the first stimulus was presented at the right index finger, and to the extreme left and up to respond that the first stimulus was at the left index finger ("right"-, and "left"-responses). In case of a "movement error", participants obtained only feedback about their error without responding, and the trial was repeated later in the experiment. Movement errors were defined by a root-mean-squared error > 45% in stroke duration or length (targets 1000 sec and 280 mm).

If the comparison stimulus at the stationary finger had to be given prior to the standard stimulus at the moving finger (negative SOA), we had to predict when the moving finger would reach the target position for the vibrotactile stimulus (-70, 0, 70mm). We modeled finger movement using the following function (based on data in [14]).

$$x_t = -\frac{1}{2} A_M \cos\left(\frac{2\pi t}{T}\right) \quad (1)$$

x_t: position of moving finger; T: period of 2 strokes (=2 seconds); t: time from stroke onset; A_M: movement amplitude (estimated as 310 mm from data in [14]). We calculated at which position the moving finger would be, when it required the time span specified in the SOA to move to its target position. When the moving finger was at that position, we delivered the stimulus at the stationary finger. The stimulus at the moving finger was then given after the exact SOA, leading to some jitter of stimulus presentation around the proper target position. In order to treat negative and positive SOAs similarly, we mimicked the positional jitter (Gaussian distribution, standard deviation from data) also when the stimulus at the moving finger was delivered first.

In the stationary control trials participants also initially brought their "moving index" finger to a left or right landmark. Afterwards another landmark appeared at a crossed, uncrossed or in-between position relative to the other index finger (-70, 0, or 70mm), and participants moved the finger to that position. After a delay of about 1000 ms, the vibrotactile stimuli were delivered to "moving" and stationary finger, and participants again responded at which finger the stimulus was presented first.

The entire experiment started with movement practice. Initially, participants trained only the movement in synchrony with the metronome. Afterwards, the movement was combined with the TOJ task. Each practice phase ended when the movement was performed without error for five times in a row. The proper experiment was divided into 12 blocks of movement conditions and 12 blocks of stationary control conditions (alternating). Half of the participants started with a movement block, the other half with a control block. One control plus one movement block were a "set" in which one finger was constantly the stationary finger, whereas the other finger was the moving finger. The assignment of left and right index fingers changed between sets. Each movement block comprised two trials per SOA, Present Position and Position Change conditions, i.e. 12 x 3 x 2 x 2 =144 trials in random order; each control block comprised two trials per SOA and Present Position condition, i.e. 72 trials. A set of blocks lasted about 45 minutes, the entire experiment about 9 hours (6-10 sessions) and included 2592 trials.

D. *Data Analyses*

We determined condition-wise individual psychometric functions as the percentages of trials in which the stimulus at the stationary finger was perceived first. Initially, we fitted cumulative Gaussian functions using Bayesian methods in psignifit 4 [15]; σ assessed the JND. We reanalyzed the data in the stationary crossed and the movement conditions using an adaptation of the flip model [1]. We assumed that the order judgment probability (p_c) was flipped from the basic probability in uncrossed conditions (p_u) as follows:

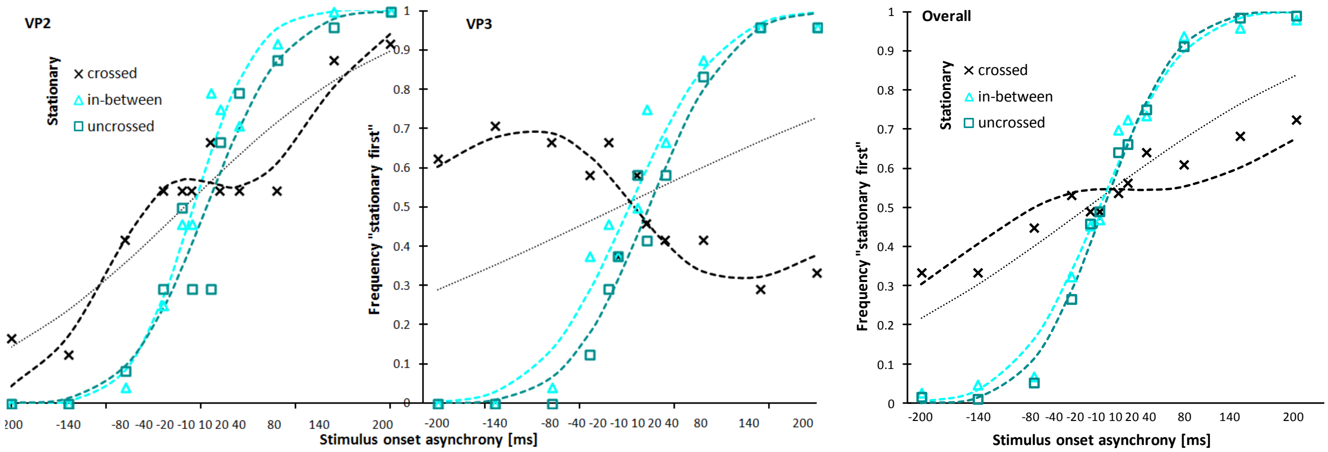

Figure 2. Psychometric functions and model fits for stationary control conditions of two exemplary participants (left) and averaged data (right). For all conditions fits to a cumulative Gaussian are depicted. For the crossed condition, we included in addition to the Gaussian fit (dotted line) also the fit to the flip model (broken line). Models in the overall data part are based on the averaged parameters from the individual fits, not on averaged response frequencies.

$$p_c(i) = f_m(\mathrm{i})\left(1 - p_u(i)\right) + p_u(i)(1 - f_s(\mathrm{i})) \qquad (2)$$

$$f_s(\mathrm{i}) = A_s e^{-\frac{(i-d)^2}{2\sigma_f^2}} \qquad f_m(\mathrm{i}) = A_m e^{-\frac{(i-d)^2}{2\sigma_f^2}} \qquad (3)$$

f_m: flip probability of judgment from "moving first" to "stationary first" and f_s: from "stationary first" to "moving first"; i: the stimulation interval = SOA; A_m and A_s: peak flip amplitudes of Gaussian functions; d: transition along time axis; σ_f: width of time window of flip. Note that the original model contained another constant and was defined for flips in left-right judgments. We estimated the free parameters analogously to [1]: The probabilities p_u(i) were calculated from the fit of a cumulative Gaussian function to the pooled data from all participants in the uncrossed and in-between stationary control conditions. Then, we used least-squares methods to estimate the four individual free parameters based on the response frequencies (assessing the p_c) for each movement and the stationary crossed condition. Parameter estimates were confined to be within reasonable boundaries (A_m, A_s: 0...1, d: -200...200, and σ_f: 0...300). These parameters were entered into further analyses.

III. Results

A. Psychometric functions and JNDs

Fig. 2 and 4 depict exemplary and average psychometric functions including model fits. In Fig. 2 the cumulative Gaussian function well fits the depicted data from the stationary uncrossed and in-between condition, but not that from the crossed condition, for which, hence, also the flip model is presented. In Fig. 4 data points from movement conditions are shown with fits of the flip model only.

As a gross measure of TOJ performance and crossed-hands deficits we first analyzed JND estimates from Gaussian fits (Fig. 3). As can be seen in Fig. 2 (center) in cases where the flip model applies better than the Gaussian function, JND estimates can be very large, indicating crossed-hands deficits. One may question whether such large JND estimates are still meaningful. We, hence, analysed TOJ performance in parallel through percentage of correct responses (independent of SOA). However, these analyses yielded the same conclusions as the JND analyses. We analyzed JNDs by two ANOVAs: one on stationary conditions (variable: Present

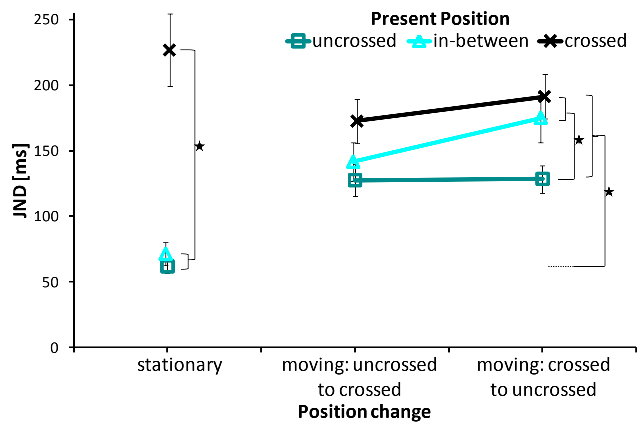

Figure 3. Average JND estimates from Gaussian fits and standard errors. Significant differences are indicated by asterisks.

Position), the other on movement conditions (variables: Position Change, Present Position). We finally compared movement conditions to the crossed and uncrossed stationary condition using t-tests. JNDs differ between the three stationary control conditions, $F(2, 14)=28.3$, $p<.001$. According to Bonferroni-corrected post hoc t-tests JNDs were not significantly different for uncrossed and in-between conditions ($p>.5$), but in both cases significantly lower ($ps<.01$) than in the crossed condition, indicating a crossed-hands deficit. For the movement conditions JNDs significantly differed between the Present Positions, $F(2, 14)=11.7$, $p<.01$, but not as a function of Position Change, $F(1, 7)=3.7$, $p=.10$, interaction: $F(2, 14)=1.2$, $p=.32$. Bonferroni-corrected t-tests show that JNDs were lower in uncrossed conditions than in crossed ($p<.01$) and in-between conditions ($p=.04$), between which they did not significantly differ ($p=.35$). Finally, t-tests showed that, JNDs in each movement condition were significantly higher than in the stationary uncrossed condition ($ps\leq.01$), but not significantly different from the stationary crossed condition ($ps>.14$, all Bonferroni-corrected). This suggests a crossed-hands deficit in each movement condition.

Parameters of flip model of crossed-hands performance

Averages of three of the parameters are depicted for each movement and the stationary crossed condition in Fig. 5. We analyzed the width of the time window of flip σ_f ("stimulus

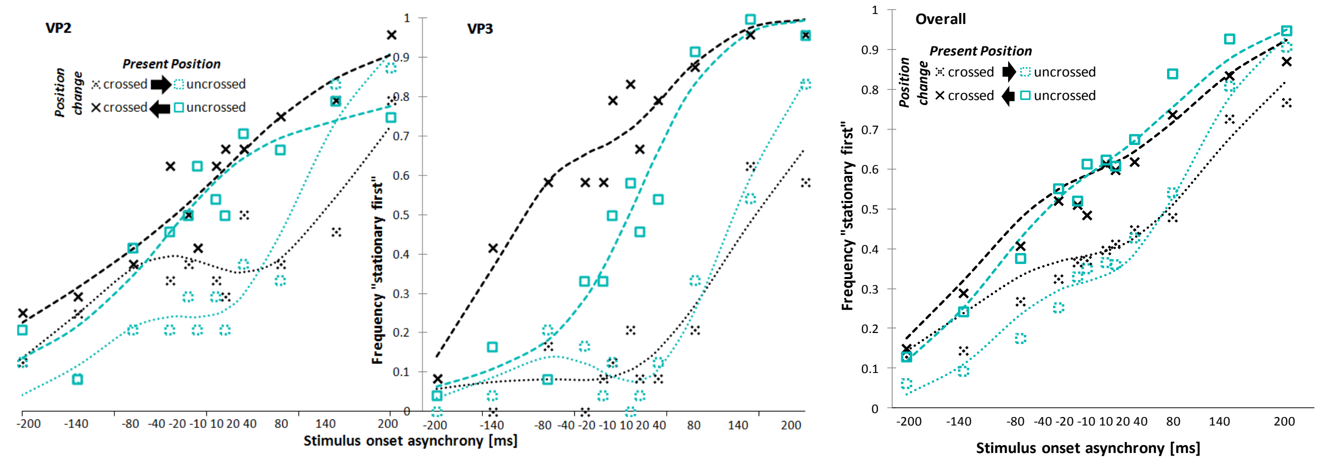

Figure 4. Psychometric functions and model fits (flip model) for conditions with finger movements for the same two exemplary participants (left) as in Fig. 2 and for averaged data (right). For reasons of clearness the in-between conditions are not included. Models in the overall part are based on the averaged parameters from the individual fits, not on averaged response frequencies.

interval of temporal confusion") by another two-way ANOVA on movement conditions (Fig. 5, bottom). Effects of Position Change, $F(1, 7)$=0.1, p=.75, and the interaction, $F(2, 14)$=0.7, p=.50, were not significant, but the main effect of Present Position, $F(2, 14)$=5.5, p=.018. Post-hoc t-tests (Bonferroni-corr.) suggested that the time window of flip was smaller in the uncrossed condition as compared to in-between (p=.05). The other two differences were not significant (ps >.22). Three further t-tests between the stationary crossed condition and each Present Position in the movement conditions showed a trend of a smaller window in the uncrossed movement conditions (p=.054), but no significant effect (other ps >.29).

Finally, we analyzed the peak flip amplitudes in an ANOVA with the three variables Present Position, Position Change, and Flip Direction (A_m: number judgment reversals from "moving first" to "stationary first" vs A_s: number reversals from "stationary first" to "moving first"). There was no significant main effect, Present Position: $F(2, 14)$=0.6, p=.57, Position Change: $F(1, 7)$=0.5, p=.49, and Flip Direction: $F(1, 7)$=0.02,p=.88 and also most interactions were not significant, Present Position X Position Change: $F(2, 14)$=0.7, p=.51, Present Position X Flip Direction: $F(2, 14)$=1.0, p=.37 three-way interaction: $F(2, 14)$=1.3, p=.30. However, the interaction between Position Change and Flip Direction was significant, $F(1, 7)$=12.9, p=.009, indicating that during movements from uncrossed to crossed hand positions participants' flip probability from "moving first" to "stationary first" was higher than from "stationary first" to "moving first", whereas it was exactly the other way round during movements from crossed to uncrossed hand positions. Using t-tests we further, compared the two flip amplitudes in the stationary crossed-hands condition to another and to the corresponding average flip amplitudes in the moving hands conditions separated by Position Change. In the stationary condition the two peak flip amplitudes were not significantly different, $t(7)$=1.0, p=.36, and in four Bonferroni-corrected t-tests the flip probabilities did not significantly differ between the stationary and the movement conditions (each p>.10).

IV. Discussion

The crossed-hands deficit in temporal order judgments

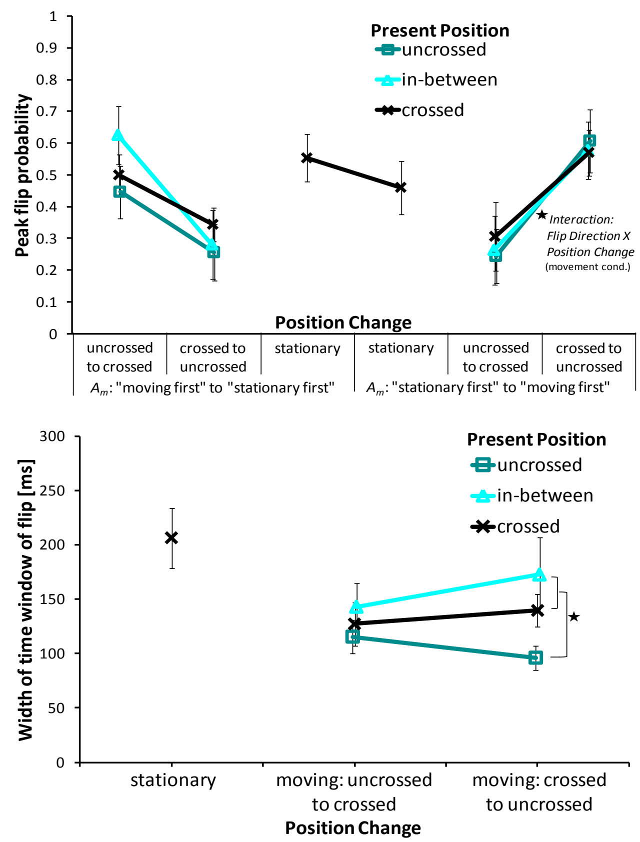

Figure 5. Average estimates of peak flip probabilities Am and As (top) and of the width of the temporal window of flips and standard errors. Significant differences are indicated by asterisks. The parameter lateral transition is not depicted, because in neither condition it significantly differed from zero (ps>.45), nor did it significantly differ between movement conditions (ANOVA: Present Position, Position Change; ps> .27).

has been explained by interferences between external and body-centered spatial coordinates of touch localization. Previous studies [3-5] have shown that before a crossing or uncrossing movement present and future (predicted) hand positions influence touch localization. Here, we measured TOJs during movement, and found pronounced crossed-hands deficits both before future and after past crossed-hands postures, and yet larger deficits when hands were presently crossed (assessed by JNDs; note that for movements without hand crossings particularly low JNDs were reported [16]). We conclude that during movement present, future, and past limb coordinates influence touch localization simultaneously. We suggest that the dynamic updates of external coordinates during movement include not only predictive processes, but also processes that preserve the recent past.

The crossed-hands deficits that we observed in the movement conditions and in the stationary crossed-hands conditions were well fit by the flip model from [1]. Because, the model has four free parameters, the good fit may not provide a strong argument in favor of the model. However, the outcomes for the four model parameters were clear-cut (one being irrelevant, and the other three linking to two different single variables each), and thus validate the model. According to the model, flips of judgments occurred for stimulus intervals of about ±150 to 200ms (temporal window) when the hands were presently crossed. The temporal window was smaller, ±100 ms, when the hands had been crossed in the recent past or were about to be crossed in the immediate future. Thus, the results for the temporal window resemble those for the JNDs. In line with the explanations of the crossed-hands deficits in [1, 6, 10, 11], these results suggest that more pronounced interferences between body-centered and external spatial coordinates are characterized by the time required to resolve them. The other central finding from the model is that the overall flip probabilities−when combined for both types of judgment flips−did neither depend on the present hand positions nor on the position change. This suggests that the extent of interferences between the coordinate systems does not affect the probability of misjudgments−only the temporal window.

However, there was an interaction between the flip direction and the position change: When moving from uncrossed-to-crossed positions people mainly flipped from moving first to stationary first judgments, whereas moving from crossed to uncrossed conditions comes along with a majority of flips from stationary first to moving first judgments. Similar effects were not observed in the stationary condition. This effect was not expected. It could represent a response bias in case of coding interferences: If people are not certain, which stimulus was first, they might have tended to respond “stationary” after a movement to a crossed hand position and “moving” when finishing at an uncrossed position. A trivial, but possible explanation for such behavior could be that the “stationary” response button was closer to the moving hand after a crossing movement (after the left hand had crossed the right hand, it ended close to the right “stationary” response button and vice versa when the right hand moved), and the “moving” response button was closer to the moving hand after an uncrossing movement. However, this explanation still needs to be tested.

Note also that the response mode here was overall likely more complicated than the common response mode to move the stimulated finger, and there is evidence suggesting that the response mode modulates the crossed-hands deficit [17]. However,, a review of the literature also shows that the deficit stably occurs under a very wide variety of response modes [1]. Thus, we can assume that also with our specific response mode we primarily assessed the typical crossed-hands deficit.

Taken together, we found evidence corroborating the flip model of crossed-hands deficits [1], and evidence demonstrating that more pronounced deficits come along with higher time requirements to resolve interferences between coordinate systems. Finally, we found evidence that spatial codes during movement refer to both predicted, future and preserved, past body postures. Predictive processes are widely acknowledged to support the planning and execution of movements, e.g. by allowing for anticipatory adjustments or attenuation of expected sensory input [18]. Preserved past information may also be useful, to support a proper post-hoc interpretation of recent past events at the skin.

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