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Just visual context or part of the gesture? The role of arm orientation in bent pointing interpretation

Lisa-Marie Krause *, Oliver Herbort

Department of Psychology, Julius-Maximilians-Universität Würzburg, Germany

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ABSTRACT

Pointing gestures can take on different shapes. For example, people often point with a bent wrist at a referent that is occluded by another object. We hypothesized that while the extrapolation of the index finger is the most important visual cue in such bent pointing gestures, arm orientation is affecting interpretations as well. We tested two competing hypotheses. First, the arm could be processed as a less reliable but additional direction cue also indicating the referent. Consequently, the index finger extrapolation would be biased towards the arm direction (assimilation effect). Second, the arm could be perceived as visual context of the index finger, leading to an interpretation that is repulsed from the arm direction (contrast effect). To differentiate between both, we conducted two experiments in which arm and finger orientation of a virtual pointer were independently manipulated. Participants were asked to determine the pointed-at location. As expected, participants based their interpretations on the extrapolation of the index finger. In line with the second hypothesis, the more the arm was oriented upwards, the lower the point was interpreted and vice versa. Thus, interpretation pattern indicated a contrast effect. Unexpectedly, gestures with aligned arm and index finger deviated from the general contrast effect and were interpreted linearly compared to bent gestures. In sum, the experiments show that interpretations of bent pointing gestures are not only based on the direction of the index finger but also depend on the arm orientation and its relationship to the index finger orientation.

Pointing gestures are as manifold as the situations in which they are used. Sometimes they are accompanied by verbal deixis, sometimes not. Sometimes only a waving hand is used to just roughly indicate a direction. Sometimes the head is only slightly pointing towards something or someone when the pointer does not want to attract attention of third parties. In some cultures, nose or lips are used for pointing (Cooperrider & Núñez, 2012; Wilkins, 2003). However, using the arm, hand, and index finger is probably one of the most common ways to direct the attention of interlocutors to a distant referent – especially in western cultures. As pointing gestures are one of the pillars of human interaction, a growing number of studies focused on how pointing gestures including arm, hand and index finger are perceived and how various factors like distance or observer perspective are influencing their interpretation (cf., Herbort & Kunde, 2016; Krause & Herbort, 2021; Mayer et al., 2020; Wnuczko & Kennedy, 2011). Most of those studies examined a specific arm-hand configuration for pointing. That is, the arm, hand, and index finger form a straight vector, so that all segments generally point in the same direction. In the following, we refer to this type of pointing as straight pointing. Straight pointing gestures are typically used when high precision is needed and even toddlers learn to use them before they start speaking (Tomasello et al., 2007). When seeing the pointer from a sideward perspective, observers interpret straight gestures by extrapolating the vector described by the line between shoulder and index finger for identifying the assumed referent location (Herbort & Kunde, 2016; Taylor & McCloskey, 1988; Wnuczko & Kennedy, 2011). Note that those extrapolations are not linear even over short distances but biased towards the pointer's midline (Bouma & Andriessen, 1968; Herbort & Kunde, 2016).

However, people also point with other arm-hand configurations. We refer to these gestures as bent points. For examples, bent points are sometimes used to point around objects that are in front of the referent. In contrast to straight pointing gestures, bent points have been rarely considered in research literature so far. Therefore, only little is known about how they are perceived and what guides and affects their interpretation. Holladay et al. (2014) were among the first to examine the perception and advantages of bent pointing gestures in human-robotic interaction. They noted that in some situations, the extrapolation line of a straight pointing gesture may intersect with the referent but also

* Corresponding author at: Department of Psychology, Julius-Maximilians-Universität Würzburg, Röntgenring 11, 97070 Würzburg, Germany.
E-mail addresses: lisa-marie.krause@uni-wuerzburg.de (L.-M. Krause), oliver.herbort@psychologie.uni-wuerzburg.de (O. Herbort).

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with distractor objects – resulting in ambiguous pointing gestures. To mend this problem, they suggested to use bent points to position the robot's hand so that the extrapolation line intersects exclusively with the referent. They found that human observers understood such bent robotic pointing gestures to one of two adjacent objects better than straight points. Additionally, observers' confidence in their interpretation increased. In summary, bent pointing gestures may affect pointing perception by allowing to adapt the hand position and orientation to the current situation.

In another study by Kobayashi and Yasuda (2015), several potential referents were placed on a table, some before and some behind an opaque wall from the view of the pointer. If the pointer used bent points, observers who viewed the scene from the side identified the referent more frequently when objects were behind the wall. Apparently, the bent point let observers to also consider occluded objects for referent identification. In contrast, when pointing with a straight gesture, objects behind the wall were less likely to be considered as potential referents. The authors concluded that using a bent gesture acts as a cue that something unusual should be considered when interpreting the gesture, since a straight configuration is obviously not sufficient (Kobayashi & Yasuda, 2015). Hence, according to this interpretation, the arm posture itself may have carried information.

Above, two different ways have been suggested of how the arm configuration could affect pointing interpretation. First, the arm determines the position of the hand and index finger. Thus, the arm can be used to position the hand and index finger in a way that reduces the number of objects that intersect the hypothetical line protruding from the index finger (Holladay et al., 2014). Second, the arm configuration might convey rather abstract meaning about which potential objects should be considered (e.g., in front vs. behind a barrier; Kobayashi & Yasuda, 2015). In both cases, a change in the gesture is realized by reconfiguring arm, hand, and index finger. However, it is possible that the relative orientation of arm, hand, and finger does not only determine the origin of the vector defined by the index finger or conveys some abstract meaning but also affects how participants extrapolate from the pointing finger.[1] In this paper, we heed two possible effects of the arm direction on pointing perception (see Fig. 1).

First, the arm could be processed as an additional direction cue, which is integrated into the interpretation. Hillis et al. (2004) found that participants combined simultaneously presented slant information provided by two different cues (disparity and texture) to a final estimation. In detail, both cues were evaluated with respect to their reliability, correspondingly weighted and integrated optimally into the final estimation. Transferred to bent gestures, the arm orientation would be perceived as indicative for the referent even though the arm orientation is deviating from that of the finger. It can be assumed that the finger is considered a much more reliable cue than the arm, resulting in a judgment mainly based on the finger but also to some small extent on the arm orientation. Therefore, the interpretation would show an *assimilation effect*, as the extrapolation of the finger direction as its main determinant should be biased towards the arm orientation (Fig. 1).

Second, the arm could be perceived as visual context which embeds the index finger orientation and therefore not as directly pointing towards the referent. The orientation of visual context affects the perception of a referent stimulus' orientation typically resulting in contrast effects (Clifford, 2014; Gibson, 1937). For example, in one experiment, a referent line flanked by two inducer lines was presented (Gibson, 1937). Either the flanker lines or the referent was vertically oriented while the respective other component was presented slightly tilted from vertical orientation. Participants fixated the referent for several minutes. Afterwards, when a probe with all lines being objectively vertical was shown, participants reported the center line to be tilted in the direction opposite to the previously shown flanked lines. The effect was reliably replicated in subsequent experiments, even when the fixation time was radically reduced to a few milliseconds or the design slightly changed, e.g., varied spatial dimensions, amounts or position of inducer lines (cf., Clifford, 2014; Westheimer, 1990). In case the estimation of the referent location would be mainly based on the index finger orientation but be biased away from the arm orientation. Thus, interpretations would show a contrast effect (Fig. 1).

To examine whether the arm is considered to convey directional information or whether it constitutes the visual context for the pointing index finger, we conducted two experiments. In both experiments, we orthogonally manipulated the arm and finger orientation of a virtual pointer. Participants had to mark the pointed-at positions on a vertical line. Additionally, the distance between pointer and line was varied as extrapolations of the pointing finger are typically non-linear (Herbort & Kunde, 2016; Herbort & Kunde, 2018). By using multiple distances, non-linearities become apparent and can be considered when interpreting the data.

1. Experiment 1

The experiment was conducted to answer the question how the arm orientation in bent pointing gestures is altering the interpretation of pointing gestures. If the arm is processed as visual context, we expect a contrast effect. If the arm is considered as a cue carrying directional information, we expect an assimilation effect. If the arm affects the perceived orientation of the index finger, we expect that the effect of the arm manifest over various distances between pointer and the pointed-at line. Additionally, as observed in previous studies, we expect the interpretations to be increasingly biased towards a horizontal axis with increasing pointer-referent distance (e.g., Herbort & Kunde, 2016).

1.1. Method

1.1.1. Participants

We recruited 40 participants aged 19 to 62 years (mean age = 28, *SD* = 10.6) online from the participant pool of the Department of Psychology of the Julius-Maximilians-Universität Würzburg. Of those who responded, 27 were female, 10 were male, one identified as "other". Thirty-seven participants reported to be right-handed and one left-handed (two did not answer). All provided informed consent and received 6.50 € as monetary compensation for voluntary participation. Both reported experiments were in line with the Declaration of Helsinki and approved by the department's ethics committee (GZEK 2019-20).

Based on an unpublished prior study ($n = 37$) conducted at our lab, we bootstrapped 1000 datasets to simulate repeated-measures ANOVAs with factors finger orientation, arm orientation, and distance for various sample sizes (15, 20, 25, 30, 35, 40). We aimed at a power of 90 % detecting a main effect of finger orientation as well as an interaction between the orientations of finger and arm. For calculations, we used a customized R script. The simulations showed that a sample size of $n = 15$ allows a detection of the critical interaction with a power of $1\text{-}\beta = 0.90$ ($\alpha = 0.05$) and that a sample size of $n = 40$ is sufficient to detect an effect of arm orientation with a power of $1\text{-}\beta = 0.91$ ($\alpha = 0.05$). Based on these calculations, we decided to collect data from 40 participants.

1.1.2. Stimuli and apparatus

The study was programmed with PsychoPy (version: 2020.2.10) and conducted online via Pavlovia. Stimuli were generated with an isometric perspective via Unity (version: 2019.3.10f1) and screenshotted for the experiment. Fig. 2 depicts sample stimuli. For stimulus description, we use the metric values used to create the virtual scene. Actual values depended on the participants screen sizes, but we collected no information about those. Each stimulus showed a male, computer-generated

[1] In this paper, we exclusively concentrate on bent gestures in which only the wrist is bent so that hand and index finger are always extended in a straight line pointing in the same direction. For the sake of readability, we conflate both under the term 'finger'.

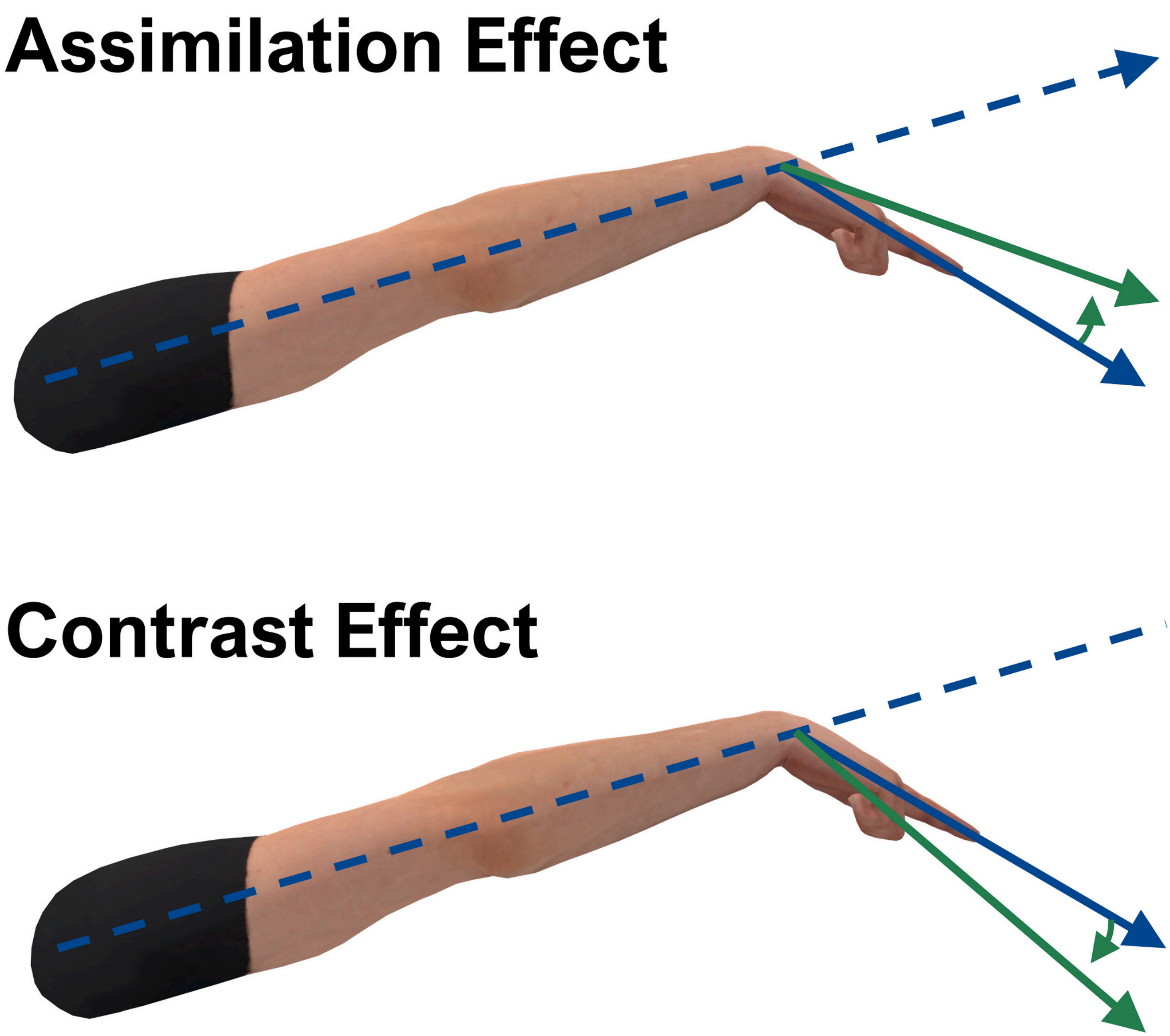

Fig. 1. Possible effects of arm and hand/index finger configuration on pointing interpretation
Note. The two hypothesized effects defined by the relationship between arm and hand/index finger orientation. If the arm is perceived as additional direction cue, the interpretation should be biased towards the arm direction (assimilation effect). If the arm is perceived as visual context cue, the finger extrapolation should be repulsed from the arm orientation (contrast effect).

pointer (height: 192 cm, shoulder-to-fingertip-distance: 76 cm) pointing always with his right arm, and index finger on a 4.2 m high, vertical black line in front of him. The pointer was always looking straight ahead. Note that regardless of the screen size or whether pointer or line were perceived as actually having the mentioned height, the relation between all components always remained constant. To avoid the interpretations to be influenced by central tendencies, the outstretched fingertip was at the same screen position in every condition. Therefore, the pointer's arm and body position varied slightly between conditions depending on finger and arm orientation. Note that distance between the fingertip and the vertical line was not affected by arm or finger orientation. A plain grey surface served as background. Participants saw the pointer always from his right side so that important aspects of the pointing gesture like the lateral pointing arm, hand, and finger and thus, their orientation were readily visible.

On the participants' screens, the stimuli were positioned vertically and – for the middle distance also horizontally – centred on a white surface. Stimuli of the shorter or longer distance were correspondingly shifted further to the left or right to keep the fingertip position constant on screen. Stimuli were always presented in full screen. The height of the pointer made up 45.1 % of the screen height, with the participants' screen height being the scaling factor. A moveable dark red triangle on the vertical line, which appeared as soon as and where participants clicked on the vertical line, served as marker for the assumed pointed-at location.

1.1.3. *Procedure*

Before the experiment started, participants received instructions and completed five trials of training. At each trial onset, a blank white screen was presented for 500 ms. Then, a stimulus appeared with the pointer pointing at an invisible referent on the line. When clicking on the assumed pointed-at location on the line with their computer mouse, the click position was marked with a red triangle. The triangle could be further adjusted by clicking on another location or by moving it with the left mouse button being pressed. Participants confirmed their judgements by pressing the space bar. Then, the next trial started.

The experiment was structured in three blocks, which varied in distance between the pointer's fingertip and line (25 cm, 100 cm, and

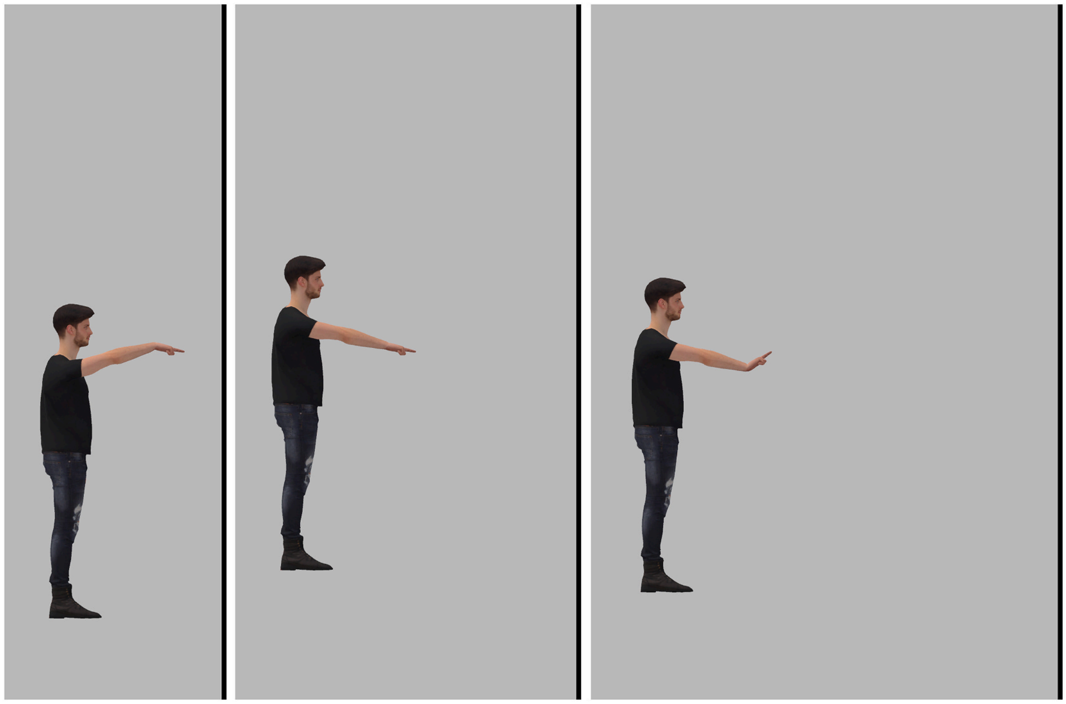

Fig. 2. Example Stimuli
Note. In all conditions, the pointer's index fingertip remained at the same location on screen. Therefore, the pointer's position slightly varied. A. Arm orientation: 15°, finger orientation: −15°, distance: 25 cm B. Arm: −15°, finger: −15°, distance: 100 cm C. Arm: −15°, finger: 30°, distance: 175 cm.

175 cm), and were presented in pseudo-random order.[2] Every combination of arm orientation (−15°, 0°, 15°) and finger orientation (−30°, −15°, 0°, 15°, 30°) was presented 10 times in each block in pseudo-random order. Participants were invited to take a self-paced break between all blocks. Altogether, the experiment consisted of 450 trials and lasted on average 29 (SD = 13.8) minutes.

1.1.4. Data reduction

We operationalized interpretations by calculating the angle between fingertip height and vector from pointer's fingertip to the position marked by the participant (Fig. 3). Positive values denote upward extrapolations. Considering that interpretations of pointing gestures originate at the pointer's index fingertip when seeing the gestures from the side (Krause & Herbort, 2021), this operationalization has three main advantages in the context of the present experiment. First, participants' responses can be directly compared to the index finger orientation. Second, it allows us to easily compare interpretations with different distances. Third, non-linear extrapolations are directly marked by an effect of distance. In case of linear extrapolation, angles should be identical across distances.

The five initial training trials were removed beforehand. All trials in which a marked estimated referent location of an observer on the line deviated >2 SD from his individual cell mean of that specific condition (distance, finger and arm orientation) were omitted from the analyses (2.4 % of all trials). A total of 17,566 trials (out of 18,000) remained in the analyses.

[2] To pseudo-randomize blocks and trials, we used the full random loop function in PsychoPy. For example, all stimuli within the same distance condition (e.g., 25 cm; 5 Hand orientation × 3 Arm orientation) were ten times (repetition = 10) within the sample and are consecutively picked without replacement.

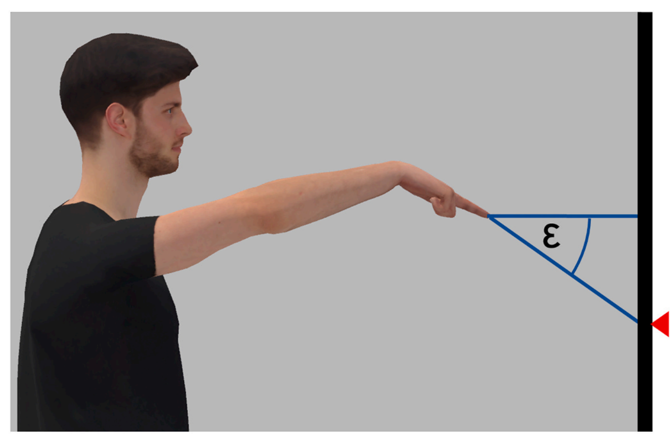

Fig. 3. Graphical Representation of Dependent Variable
Note. Calculation of the dependent variable as angle ε between the participant's judgment (red triangle to the right of vertical line) and finger height. Positive values indicate interpretations above fingertip height, negative ones below it. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

1.2. Results

Interpretations were entered in a repeated measures ANOVA with within-subject factors arm orientation, finger orientation, and distance. Greenhouse-Geisser corrected p-values are reported to correct sphericity violations. Participants' judgments depending on arm and finger orientation for each distance are shown in Fig. 4.

Not surprisingly, the interpretation mainly depended on finger orientation, $F(4,156) = 755.31$, $p < .001$, $\eta_p^2 = 0.95$, GG-ε = 0.33. The higher the finger was oriented, the higher the interpretation. However, the interpretation was also significantly influenced by arm orientation, $F(2,78) = 4.22$, $p = .035$, $\eta_p^2 = 0.10$, GG-ε = 0.65. Here, the lower the arm

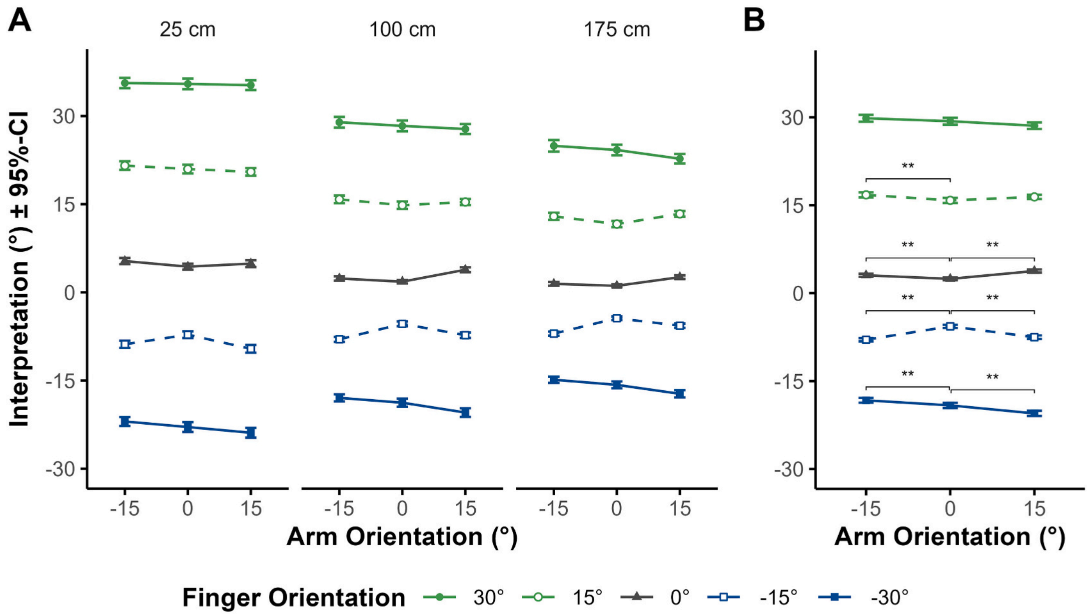

Fig. 4. Gesture interpretation.
Note. Negative values in arm and finger orientation indicate a downward oriented arm and finger, respectively. Negative values in interpretations indicate interpretations below the fingertip height. Error bars show 95 % confidence intervals. A. The figure shows the participants' interpretation for each arm orientation and finger orientation, separately for all three distances. B. Follow-up paired sample *t*-tests for the interaction between arm and finger orientation, * $p < .05$, ** $p < .01$.

was oriented, the higher was the estimated referent location, indicating a contrast effect. This main effect interacted with finger orientation, $F(8,312) = 26.10$, $p < .001$, $\eta_p^2 = 0.40$, GG-ε = 0.63. The interaction can be described as follows: Higher arm orientations resulted in lower interpretations, except for straight gestures where arm and finger orientation coincide, especially in the −15°/−15° and 15°/15° conditions.

Furthermore, lower referent positions were indicated for higher distances, $F(2,78) = 42.22$, $p < .001$, $\eta_p^2 = 0.52$, GG-ε = 0.78. Finger orientation further modulated the main effect of distance, $F(8,312) = 87.52$, $p < .001$, $\eta_p^2 = 0.69$, GG-ε = 0.27. With growing distance, the effect of the finger decreased. This effect indicates that interpretations were non-linear and increasingly biased towards a horizontal axis with increasing distance. Finally, the 3-way interaction reached significance, $F(16,624) = 4.86$, $p < .001$, $\eta_p^2 = 0.11$, GG-ε = 0.60.

We further examined both, the overall contrast effect, and its apparent absence for straight gestures (henceforth: "straight pointing effect") by analyzing the interpretations for successive arm orientations. Therefore, we calculated five follow-up paired sampled *t*-tests between arm orientations of −15° and 0° as well as between 0° and 15°, separated for each level of finger orientation and adjusted with Bonferroni-Holm (Table 1). Concerning the straight pointing effect, two comparisons are of relevance: first, arm orientations −15° vs. 0° while the finger has an orientation of −15° and second, arm orientations 0° vs. 15° while the finger is oriented at 15°. Although both comparisons show visually an upward trend and are thus in contrast with the remaining downward data pattern, only the first comparison (−15° vs. 0°) reached significance (see highlighted tests in Table 1). To further examine the visually indicated contrast effect, we focus on the remaining eight comparisons. Five out of eight tests significantly showed a downward trend, one at least a marginal effect in the same direction. Thus, the results supporting the assumption that the arm orientation is affecting the interpretation, even though it is mainly based on the direction indicated by the finger. Generally, a lower arm orientation led to higher interpretations supporting the hypothesis of the contrast effect.

Table 1
Results of follow-up paired sample *t*-tests on each finger orientation level.

	Arm orientation -15° vs. 0°				Arm orientation 0° vs. 15°			
Finger	*t*	*df*	*p*	*d*	*t*	*df*	*p*	*d*
-30°	**2.89**	**(39)**	**.006**	**0.46**	**6.41**	**(39)**	**< .001**	**1.01**
-15°	**-8.03**	**(39)**	**< .001**	**-1.27**	**8.25**	**(39)**	**< .001**	**1.30**
0°	**3.37**	**(39)**	**.002**	**0.53**	**-5.20**	**(39)**	**< .001**	**-0.82**
15°	**3.91**	**(39)**	**< .001**	**0.62**	-1.60	(39)	.118	-0.25
30°	1.85	(39)	.082	0.29	2.11	(39)	.082	0.33

Note. The highlighted *t*-tests were checked for the occurrence of the straight pointing effect. The remaining comparisons give insights about the contrast effect. Adjusted *p*-values are reported. Significant tests are printed in bold.

1.3. Discussion

We examined how the arm orientation influences the interpretation of bent pointing gestures. Observers mainly derived their interpretations by extrapolating the finger direction. As expected, interpretations were not linear and increasingly biased to the mean with increasing distance. More interesting, the arm orientation changed the interpretation in line with a contrast effect. The more downward the arm was oriented, the higher observers estimated the pointed-at location and vice versa. That means, the arm in a bent pointing gesture was not processed as additional direction cue, which provides reliable information about the exact referent location, but instead as being part of the visual context of the index finger.

Additionally, we found a data pattern that we called "straight pointing effect". When the pointer's arm and finger were aligned, the data deviated from the contrast effect. The interpretations for the −15°/−15° (arm/finger) condition as well as those for the 15°/15° condition stand out as the interpretations were lower respectively higher as expected. We can offer two possible explanations. First, this effect might depend on an increased level of perceptual certainty that straight points transport in contrast to bent ones. When arm and index finger are extended in a straight line, both indicate the same direction and may be perceived as a single stimulus that indicates a direction more reliably than the index finger alone. According to a Bayesian model of pointing interpretation, more reliable stimuli are interpreted more linearly and less biased towards the horizontal axis (Herbort & Kunde, 2016). In the experiment, this would imply that interpretations of upward or downward oriented straight points result in more upward or downward interpretations, respectively, than comparable interpretations of the index finger alone – giving rise to the straight pointing effect. Second, the straight pointing effect could have resulted from a local assimilation effect. Consider that an assimilation effect might only be observed when the difference between arm and finger orientation is small (Niimi & Watanabe, 2014) and that the perceived arm and finger orientations differed somewhat from the orientations they were supposed to have. If, for example, the (nominally) 15° arm orientation was perceived as steeper than the (nominally) 15° finger orientation – although being intended to be perceived identically – a local assimilation effect could have emerged in the conditions in which arm and finger were nominally aligned. The local assimilation effect could have counteracted the overall contrast effect. Whether the arm was perceived in this way cannot be inferred from the data. However, we would not preclude this option after closer re-inspection of the stimuli. Additionally, the finding that interpretations were generally biased upwards suggests that our stimuli were not perceived exactly as intended. In summary, as the straight pointing effect could be based on an assimilation effect, it might be too early to completely reject the hypothesis that the arm is considered a directional cue.

To answer the question how the arm orientation is affecting the perceived finger orientation, it was essential to present various arm orientations with each finger orientation while the finger position on screen was kept constant. This approach had the additional benefit that central tendencies in observer's interpretations were counteracted and that the relative position of index fingertip and vertical line was constant over distance conditions. Concurrently, it introduced a confound as especially the vertical – and to lesser extent also the horizontal – pointer position depended on the arm orientation. A downward arm orientation led to higher body positions, an upward one to lower positions. We discuss this confound in more detail in the General Discussion.

Since this experiment was conducted online, we had no influence on participants' screen sizes. That is, stimuli size varied between participants depending on their technical equipment. However, reliable effects emerged despite these limitations, which speaks for the generalizability of the reported effects.

Finally, participants could have perceived the pointer as taller or smaller than the model we used for stimulus generation and scaled the perceived pointer-line distances accordingly. However, most importantly, the relationships of sizes for all pivotal stimuli components were constant over screen sizes and stimulus orientations were not affected by screen sizes. Furthermore, as Herbort and Kunde (2016) could successfully predict data for real pointer-observer dyads based on a computer experiment that resembled Experiment 1, we expect that our results would generalize to other settings despite these limitations.

2. Experiment 2

Experiment 2 was designed to replicate Experiment 1 and to test our hypotheses on the origin of the straight pointing effect. To this end, we modified Experiment 1 in two ways. First, since we assumed that perceived finger and arm orientations deviated from the objectively set orientations, we adapted arm and finger orientations to the perception of our participants. Therefore, participants in a pre-study aligned the orientation of disembodied finger and arm stimuli with Gabor patch gratings, whose orientations were identical to the rotation values of the different gesture components in Experiment 1. This should align the perceived and nominal arm and finger orientations and thus allow us to rule out potential local assimilation effects. Second, Experiment 2 contained conditions in which either only the arm or only the hand and index finger (hereinafter: finger) were seen to test our hypothesis about increased perceptual certainty.

Generally, we expected to replicate the contrast effect found in Experiment 1. In addition, we wanted to examine the origin of the straight pointing effect. Our first hypothesis stated that the outstretched arm and finger constitute a clearer directional stimulus that is extrapolated more linearly. If this is the case, we expect a) the straight pointing effect emerges although arm and finger orientation were subjectively aligned in straight gestures and b) the combined arm and finger are extrapolated more linearly than the finger alone. Our second hypothesis was that subjective differences between arm and finger orientation in nominally straight gestures in Experiment 1 might have caused a local assimilation effect. If this was the case, we do not expect a straight pointing effect in Experiment 2, because arm and finger orientations are now subjectively aligned. The isolated presentation of either arm or index finger allowed us to verify the subjective perception of all stimulus components and whether the straight pointing effect can be interpreted as an assimilation effect.

2.1. Method

2.1.1. Participants

We recruited 31 new volunteers aged 20 to 65 years (mean age = 27, *SD* = 9.4) online from our participant pool. Of 30 participants who reported their gender, 21 were female and nine were male. In addition, 26 participants reported to be right-handed and 4 left-handed (one without response). All provided informed consent and received 8.00 € as compensation.

We conducted the power analysis identically to Experiment 1, but now we used the data of Experiment 1. We aimed for a power of at least $1\text{-}\beta = 0.95$ for the 3-way interaction, which would be detectable with a sample size of $n = 20$. To get a better estimate of other smaller effects and interactions, we settled on a sample size of at least $n = 30$.

2.1.2. Stimuli and apparatus

To generate the stimulus material, we conducted a pre-study with 13 volunteers who neither participated in Experiment 1 nor 2. Participants were asked to align – depending on the condition – a disembodied arm or index finger with Gabor patch gratings with the five orientations (±30°, ±15, and 0°) used in Experiment 1. This could be achieved by rotating the arm or index finger in 1-degree steps by pressing either of two buttons on a keyboard. For each body part and Gabor patch orientation, we averaged the five rotations produced for all participants (total: 65 trials per cell). We then used these new rotation angles to generate the stimuli for this experiment, so that now the presented stimuli should be perceived as originally intended. Compared to Experiment 1, the finger and arm orientations of Experiment 2 were generally more downward (downward finger offsets compared to Experiment 1: −30°: 6.48°, −15°: 8.77°, 0°: 3.75°, 15°: 1.85°, and 30°: 2.71°; downward arm offsets compared to Experiment 1: −15°: 5.61°, 0°: 0.78°, 15°: −1.82°).

Stimuli for Experiment 2 were again generated with the same humanoid model, now with the adjusted, new arm and finger rotation angles. We followed the same procedure as described in 1.1.2 to extract the images displayed in Experiment 2. Contrary to Experiment 1, only the model's finger, arm, or both were presented. In addition to the standard gestures consisting of arm and finger, we also took screenshots in which only the finger or only the arm was visibly pointing (Fig. 5). In conditions in which only the finger was visible (Fig. 5A), the invisible arm was always horizontally oriented. To the contrary, when only the arm was visible (Fig. 5B), the invisible finger had the identical vertical manipulation rotation. Again, PsychoPy (version 2020.2.10) was used for programming and Pavlovia for conducting the study.

2.1.3. Procedure

The procedure of the current experiment resembled Experiment 1 with the following exceptions. First, we added two conditions in which either only the finger or the arm was visible. Second, we increased total trial repetitions from 10 to 14 times. Blocks differ with respect to the distance between fingertip (irrespective whether it was seen or not) and line (25 cm, 100 cm, 175 cm) and were repeated twice in pseudo-

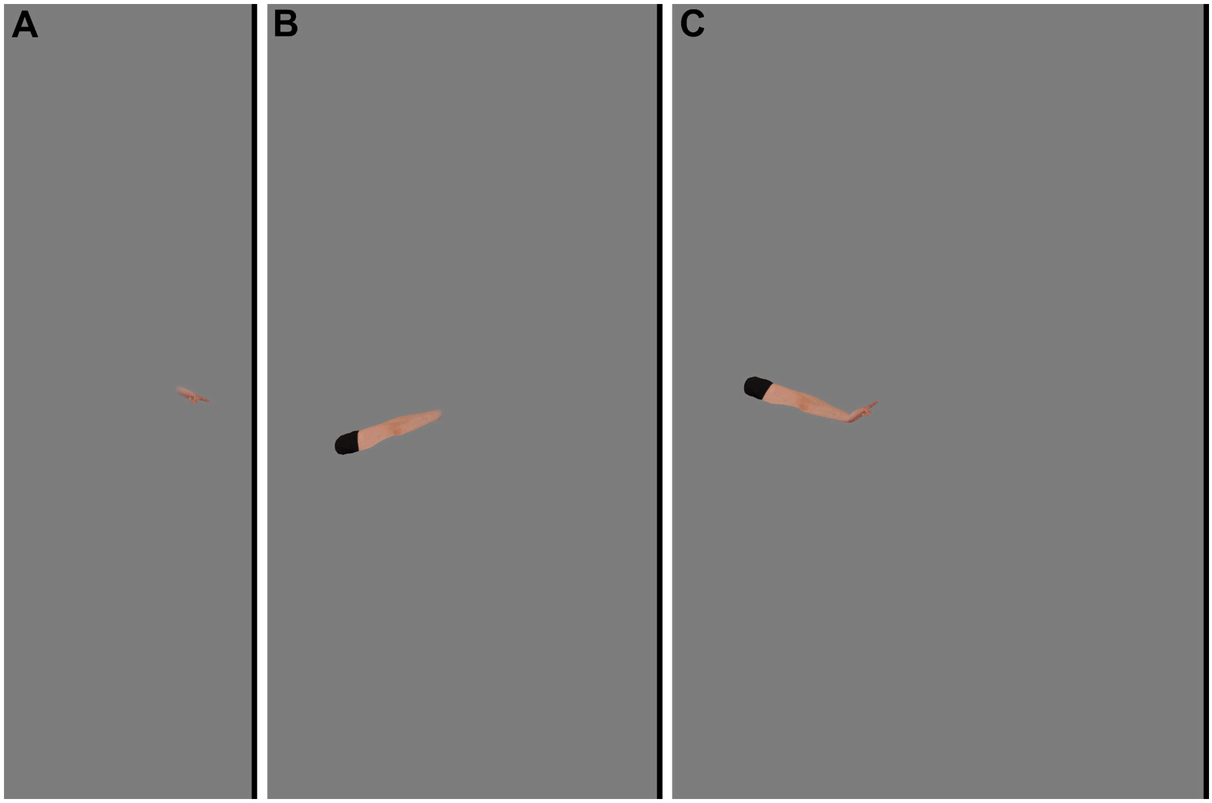

Fig. 5. Example stimuli.
Note. In all conditions, the fingertip position independently of being visible or not remained at the same screen position, resulting in varying arm positions A. Finger orientation: −15°, distance: 25 cm B. Arm orientation: 15°, distance: 100 cm C. Arm: −15°, finger: 30°, distance: 175 cm.

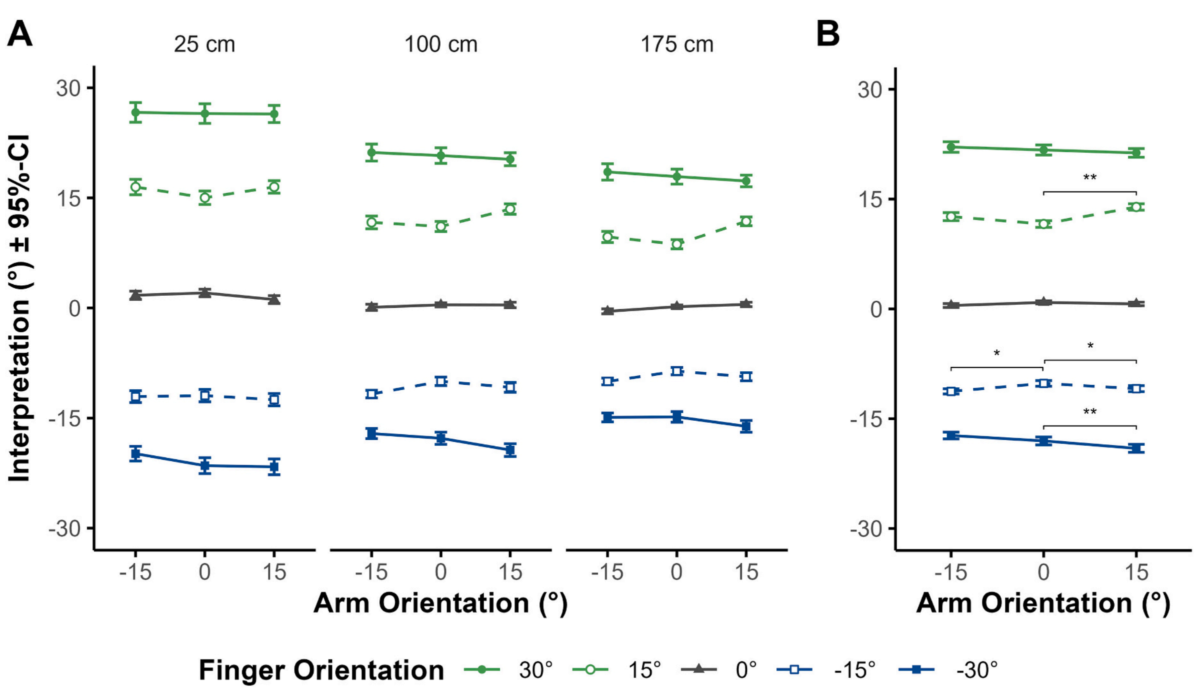

Fig. 6. Gesture interpretation.
Note. Negative values in arm and finger orientation indicate a downward oriented arm and finger, respectively. Negative values in interpretations indicate interpretations below the fingertip height. Error bars show 95 % confidence intervals. A. The figure shows the participants' interpretation for each arm orientation and finger orientation, separately for all three distances. B. Follow-up paired sample *t*-tests for the interaction between arm and finger orientation, * $p < .05$, ** $p < .01$.

randomized order. In each block, all 15 different gestures (5 Finger orientation x 3 Arm orientation) plus five finger-only and three arm-only gestures were pseudo-randomized presented seven times. Between blocks, participants were allowed to take self-paced breaks. In summary, the experiment consisted of 966 trials and lasted on average 30 (SD = 16.2) minutes.

2.1.4. Data reduction

The dependent variable was calculated as in Experiment 1. Again, initial training trials were excluded from the analysis. The outlier criterion remained the same as in Experiment 1, resulting in 1090 (3.64 %) out of 29,946 trials that were removed from the analysis.

2.2. Results

2.2.1. Arm and finger

First, we focus on the processing of the whole gesture. We calculated a repeated-measures ANOVA with within-subject factors arm orientation, finger orientation, and distance. Greenhouse-Geisser corrected p-values are reported to correct sphericity violation. Participants' interpretations of pointing gestures depending on arm and finger orientation separated for each distance are shown in Fig. 6.

The general data pattern visually resembled that of Experiment 1. However, arm orientation did not significantly influence the interpretation, $F(2,60) = 0.06, p = .828, \eta_p^2 = 0.00$, GG-ε = 0.53. The main effects of finger orientation and distance reached significance. The interpretation was the higher, the higher the finger was oriented, $F(4,120)$ = 194.92, $p < .001$, $\eta_p^2 = 0.87$, GG-ε = 0.26, and the shorter the distance was, $F(2,60) = 27.11$, $p < .001$, $\eta_p^2 = 0.48$, GG-ε = 0.81. The interpretation was again mainly guided by finger orientation.

Finger orientation and arm orientation interacted, $F(8,240) = 14.37$, $p < .001$, $\eta_p^2 = 0.32$, GG-ε = 0.50. Generally, the interpretation was higher, the lower the arm was oriented, especially for the two most extreme finger orientations (±30°). When the finger was oriented straight forward, the interpretation was not affected by arm orientation at all. Again, the data pattern exhibited the straight pointing effect. That is, if arm and finger were aligned and oriented either up- or downward, the interpretations deviated from the overall pattern of results.

The effect of distance was further modulated by arm orientation, $F(4,120) = 4.02$, $p = .016$, $\eta_p^2 = 0.12$, GG-ε = 0.61. Visual inspection disclosed that the effect of arm orientation – higher interpretation for lower orientations – was shown stronger at 25 cm and weaker at 100 cm distances, while at the longest distance of 175 cm interpretations deviated from this pattern. Here, the interpretations were higher, the more upward the arm was oriented. Again, the significant interaction of finger orientation and distance indicates that the finger orientation was not extrapolated linearly but that interpretations were increasingly biased towards a horizontal axis with increasing distance, $F(8,240) = 60.93$, $p < .001$, $\eta_p^2 = 0.67$, GG-ε = 0.27. Finally, the 3-way interaction reached significance, $F(16,480) = 2.51$, $p = .011$, $\eta_p^2 = 0.08$, GG-ε = 0.52.

Table 2
Results of follow-up paired Sample t-tests on each level of finger orientation.

	Arm orientation -15° vs. 0°				Arm orientation 0° vs. 15°			
Finger	t	df	p	d	t	df	p	d
-30°	1.21	(30)	.234	0.22	**3.83**	**(30)**	**.001**	**0.69**
-15°	**-2.20**	**(30)**	**.035**	**-0.40**	**3.01**	**(30)**	**.011**	**0.54**
0°	-0.95	(30)	.582	-0.17	1.07	(30)	.582	0.19
15°	1.66	(30)	.108	0.30	**-4.07**	**(30)**	**< .001**	**-0.73**
30°	1.33	(30)	.386	0.24	0.78	(30)	.441	0.14

Note. The highlighted t-tests were checked for the occurrence of the straight pointing effect. The remaining comparisons give insights about the contrast effect. Significant tests are printed in bold.

Comparable to Experiment 1, we further analyzed the data with follow-up paired-sample t-tests for successive arm orientations from down- to upward (−15° vs. 0°, 0° vs. 15°), for each finger orientation separately. For detailed results see Table 2. We adjusted p-values for multiple comparisons with Bonferroni-Holm correction. This follow-up analysis allows us to inspect in detail the straight pointing effect as well as the contrast effect. First, to check for the straight pointing effect, again two comparisons are interesting, arm orientations −15° vs. 0° (finger orientation: −15°) and 0° vs. 15° (finger orientation: 15°). In both comparisons, the upward trend is significant (see highlighted tests in Table 2). These results underline that straight gestures are processed differently. Since arm and finger's rotation angles were adjusted for minimizing the perceived discrepancy between both indicated orientations, this finding rather speaks against the assumption of an underlying local assimilation effect.

Second, concerning the contrast effect, we focused on the remaining eight t-tests and analyzed whether these comparisons indicate that a lower arm orientation leads to generally higher perceived pointing gestures. Although the visual inspection generally supports this hypotheses – especially for the most extreme up- and downward finger orientation – only the comparisons of arm orientations = 0° vs. 15° reached significance while the finger pointed downwards (see Table 2). Since only two out of eight t-tests show a significant effect, the contrast effect in this experiment was rather small.

2.2.2. Finger vs. arm and finger

We hypothesized that a longer finger-arm compound resulting in more linear interpretations than a shorter stimuli such as the finger alone. In this case, finger orientations should have a larger effect if the arm is visible, especially for the larger distances. To test this, we compared the trials in which arm and finger were aligned with the corresponding stimuli, in which only the finger was seen. Interpretations were entered into a repeated-measures ANOVA with factors finger orientation, arm visibility and distance. Greenhouse-Geisser correction against sphericity violations was applied. The effect of arm visibility on the interpretations for each distance is shown in Fig. 7.

As indicated by a significant main effect of arm visibility, the interpretation of the pointing gesture was 0.4° higher when the arm was visible, $F(1,30) = 4.28$, $p < .047$, $\eta_p^2 = 0.13$. Not surprisingly, the main effects of orientation and distance both reached significance. The pointed-at location was interpretated to be higher, the higher the finger was oriented, $F(2, 60) = 261.92$, $p <. 001$, $\eta_p^2 = 0.90$, GG-ε = 0.52, and the shorter the distance was, $F(2,60) = 22.73$, $p < .001$, $\eta_p^2 = 0.43$, GG-ε = 0.69.

Most relevant, the interaction of visibility and orientation approached significance, $F(2,60) = 3.75$, $p = .051$, $\eta_p^2 = 0.11$, GG-ε = 0.63. Descriptively, interpretations were biased slightly less towards a central axis if the arm was visible. Also, the effect of distance was not additionally influenced by arm visibility, $F(2,60) = 0.07$, $p = .915$, $\eta_p^2 = 0.002$, GG-ε = 0.88. Distance significantly interacted with orientation, $F(4, 120) = 39.37$, $p <. 001$, $\eta_p^2 = 0.57$, GG-ε = 0.55. With increasing distance, the interpretation of each finger orientation was increasingly biased towards the horizontal axis. Finally, the 3-way interaction did not reached significance, $F(4,120) = 1.94$, $p = .131$, $\eta_p^2 = 0.06$, GG-ε = 0.73. Thus, the data do not indicate that the aligned arm and finger are interpreted more linearly than the finger alone.

2.3. Discussion

With the second study, we aimed to replicate the data pattern of Experiment 1 indicating a contrast effect as well as shedding light on the roots of the straight pointing effect. Observer interpretations again point towards the arm orientation affecting the interpretation in form of a contrast effect. However, the effect was less pronounced in Experiment

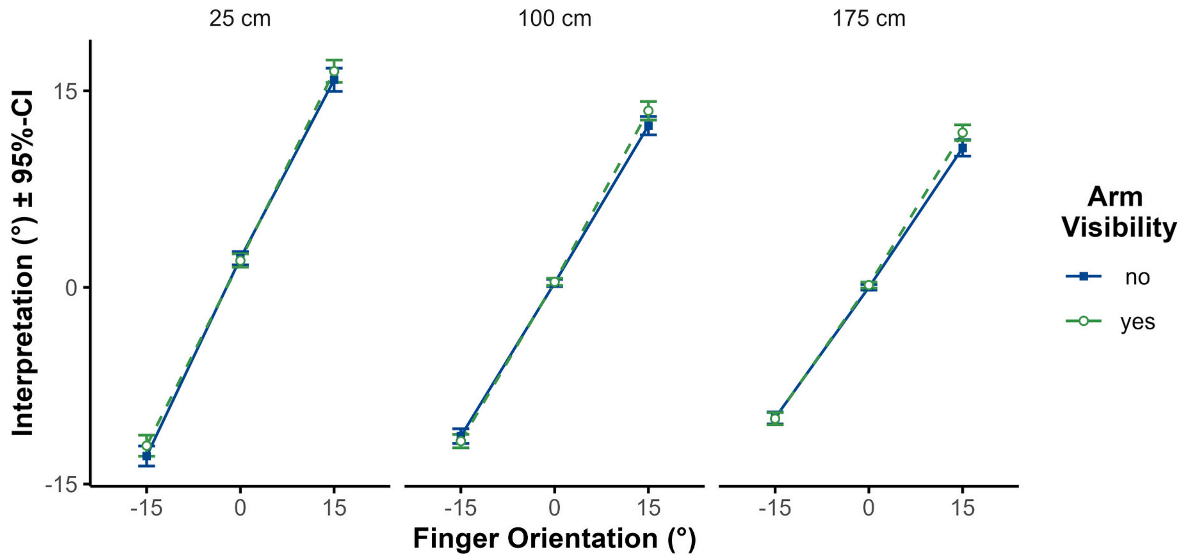

Fig. 7. Effect of arm visibility.
Note. When the arm was visible, only straight arm and finger configurations were considered. Negative values in interpretations indicate interpretations below the fingertip height. Error bars show 95 %- confidence intervals.

2. Additionally, we found the straight pointing effect when arm, hand, and finger form a straight line. The interpretations were more linear and thus, leading to significantly lower (arm/finger: −15°) respectively higher (arm/finger: 15°) estimations compared to the remaining interpretation pattern.

The reoccurring straight pointing effect after adjusting arm and finger rotations is in line with our first hypothesis stating that straight gestures provide a stronger directional cue, which should emphasis a more linear interpretation. However, a comparison of gestures with high and low perceptual certainty, that is, straight gestures versus conditions in which only the finger was seen, revealed only a marginal effect of arm visibility (p = .051). Generally, interpretations were slightly more extreme when arm and finger were seen, especially when it was pointed upwards. For downward points, this trend was rather instable and weak. Since the absolute effect of the arm is noticeable smaller than the straight pointing effect, the size of the interaction effect seems to be too small for causing the effect. Hence, our data do not support this hypothesis.

The occurrence of the straight pointing effect in Experiment 2 contradicts our second hypothesis, according to which the straight pointing effect results from local assimilations to small perceived discrepancies of arm and finger orientation. Since arm and finger orientations were adjusted in advance, perceived orientation differences should be prevented or – as the data revealed – at least clearly diminished. This notion is supported by the upward bias in interpretation being much smaller in Experiment 2 than in Experiment 1. Nevertheless, the straight pointing effect occurred, rather unaffected in its strength. Of course, arm and finger orientation were still not perfectly aligned. However, assimilations would have required the arm orientation to be perceived as being steeper than the finger. However, that is not the case. When closer inspecting the interpretations based on only finger and only arm conditions for all distances, only in upward oriented gestures the arm was perceived to be just slightly steeper. However, the effect also occurred when pointed downwards (see Supplement Table 1 and 2). Thus, we reject this hypothesis, too.

Presenting only the gesture itself (or its individual components) did not considerably reduce the confound between arm orientation and body position discussed for Experiment 1. As the shoulder was still presented as part of the arm, the pointer's body position was still implied although not directly visible for participants. Thus, its influence has probably not been fully eliminated. We return to this issue in the General Discussion.

3. General discussion

It has previously been shown that the arm-hand configuration of a pointing gesture affected how the gesture was interpreted. However, the question remained how the configuration affects how observers extrapolate from a pointer's index finger. The experiments revealed three main findings. First, not surprisingly, the interpretation of pointing gestures was mainly driven by the finger orientation. Second, Experiment 1 revealed that the arm is generally not evaluated as being a relevant part of the gesture but is rather processed as less informative part of the visual environment. Although this effect was less stable in Experiment 2, conditions with a significant effect of arm orientation pointed towards the same direction. Thus, the configuration of arm and index finger is affecting the extrapolation of the finger direction in bent gestures. Third, we found the straight pointing effect. This effect describes that straight points, in which arm, hand, and index finger are aligned, stand out from the general pattern of interpretations obtained from bent gestures. We hypothesized that the effect was either based on a local assimilation effect or on increased perceptual acuity of straight pointing gestures. However, the results of Experiment 2 rejected both hypotheses.

3.1. *Straight pointing effect*

Experiment 2 ruled out that the straight pointing effect resulted from local assimilation effects or improved visual acuity of the finger compared to the arm. Hence, we can only speculate on the source of this effect. One could argue that the reliability of the perception of the index finger orientation is not increased by the aligned arm (Fig. 6) but is decreased when accompanied with bent gestures. For example, observers might assume that bent gestures are less precise because pointers cannot "aim" over the index finger. Likewise, participants may have experienced bent gestures in situations in which gestures were less precise, for example because pointers referred to objects the pointers could not see. The reduced reliability of the index finger orientation in bent gestures may have resulted in a stronger central bias. Thus, the apparent unreliability of bent gestures may have caused the straight pointing effect.

3.2. Effect of distance

When observers interpret straight pointing gestures, they extrapolate the vector between the pointer's shoulder and the index fingertip towards potential referents (Taylor & McCloskey, 1988). Comparably to line extrapolation, findings by Herbort and Kunde (2016) suggests that straight pointing gesture interpretation also increasingly deviates from linearity over distance (Bouma & Andriessen, 1968; Herbort & Kunde, 2016). As we used angles to measure participants' responses starting from the index fingertip, linear interpretations should have remained constant over all three distances and ideally corresponded to the finger orientations. Instead, we also found non-linear data pattern when observers interpret bent pointing gestures. Again, interpretations were pulled towards a horizontal axis through the pointer's shoulder leading to less extreme judgements the further the referent line was away from the pointer. This again highlights that pointing perception can only be approximated by analyses based on the linear extrapolation of various vectors defined by the body configuration of the pointer. For a more detailed understanding, the non-linearity of pointing perception needs to be considered.

Gathering knowledge about the non-linearity bias due to increasing distances offers the opportunity to enhance pointing based communication in virtual environments or increase the legibility of pointing robots or virtual characters. For example, findings about the different strategy use of pointer and observer had led to the development of approaches for virtually adjusting pointing gestures for a better interpretation. These changes are usually only visible to the observer, so that the pointer is not affected in execution of his gesture and the danger of new biases is avoided (e.g., Mayer et al., 2020; Sousa et al., 2019). If the distance between pointer and referent is known or at least narrowed down in advance, then an extension of the adaptation algorithm by the aspect of distance bias could lead to further precision of the interpretation in virtual environments. Such considerations may also be important for programming virtual agents or robots, that exploit bent pointing gestures to position the origin of the pointing effector (Holladay et al., 2014).

3.3. Influence of shoulder position

As already mentioned, fixing the fingertip at a specific screen position in each condition introduced a confound between shoulder position and arm orientation – and to lesser extent also with hand orientation. The shoulder – and by extension the pointer's body – was higher up on the screen when the finger was pointing upwards, or the arm was oriented downwards. However, this could have been hardly avoided due to the pointer's body morphology. Thus, it is ultimately impossible to dissociate the contribution of the arm orientation and the relative positions of the body and the pointing hand to the contrast effects. From a practical perspective, this confound is unproblematic because a similar relationship between arm orientation and the finger position relative to the pointer's body applies for all human pointers.

However, we would suggest that the effects are mainly driven by the arm orientation. The main reason for our preference is that the visibility of the body often has a negligible effect on pointing interpretations. For example, Bangerter and Oppenheimer (2006) found that interpretation patterns did not depend on whether the whole pointer was shown or only the gesture (from fingertip to forearm). They concluded that the gesture components itself and not the body are relevant aspects on which observers base their interpretations. Likewise, Herbort and Kunde (2016) presented participants only the pointing gesture (from index finger to mid of upper arm) in a similar task like ours. Interpretations resembled those that were based on a pointing gesture with the pointer being completely visible. Likewise, we found similar effects in both experiments despite showing the pointer's body in Experiment 1 and hiding it in Experiment 2.

To a much smaller extend, the pointer also slightly varied in its horizontal position to compensate for different arm/hand orientations. However, we are convinced that this is not significantly reflected in vertical interpretations since different finger orientations caused comparably small height differences leading to a maximum horizontal shift of about 20 pixels while the screenshot width was 572, 896, or 1220 pixels, depending on distance condition.

3.4. Limitations and further indications

As in previous studies, the gestures were not accompanied by any verbal description and no potential referents were integrated into the design. One could argue that our experimental setups are rather artificial since observers often may use speech and common ground information to infer the correct referent. However, people regularly encounter situations that share many aspects of our experiments. Consider pointing at a star in the night sky. As an individual star is hard to describe verbally, people might initially try to rely primarily on pointing – comparable to the situation in our experiment. Once they notice that pointing fails, they might provide extensive verbal description (e.g., position of a star relative to salient constellation). Even in this case, the pointing gesture itself is central in guiding another person's attention to a specific region of the night sky. Moreover, even if speech helps to reduces pointer-observer misunderstandings, biases in pointing perception still affect the efficiency and accuracy of pointing-based communication (Herbort & Krause, 2023). Hence, as we were interested in the general mechanisms that underly the gesture perception and interpretation unbiased by further comprehension assistance or guidance, we precluded speech (cf., Herbort et al., 2020; Mayer et al., 2020). Nevertheless, we expect that the observed effects also affect situations in which pointing is accompanied by speech.

In our experiments, arm, and finger orientation as well as distance were included as variables since they have the strongest impact on pointing interpretation. However, other factors are conceivable that might influence pointing interpretation like gaze direction or head orientation. In natural pointing situations, pointers often orient their head towards the referent and fixate it. Thus, gaze direction as well as head orientation could also function as indicators, at least for narrowing down the referent location. In contrast, in Experiment 1, neither the gaze nor the head were directed or oriented differently depending on the pointing gesture, but the pointer always fixated an imaginary point straight ahead. We do not think that is a limitation. First, previous experiments indicate that especially gaze typically play only a minor role when interpreting pointing gestures. Cooney et al. (2018) found no significant effect between conditions in which the pointer was wearing sunglasses or not, indicating that observers were unaffected by gaze. The evidence for the importance of head direction is mixed. On the one hand, Butterworth and Itakura (2000) revealed head orientation contributed more to accurately identifying – especially the inner – objects on a horizontal line in front of pointer and observer compared to pointing, at least in adults. On the other hand, in a study by Herbort and Kunde (2016), the pointer's head orientation was manipulated independently of the pointing gesture. The effect of head orientation affected the interpretations only marginally. When only distances were considered that are comparable to the ones used in Experiment 1, a change in head orientation of 10° resulted in shifts in interpretations of about 1 mm (Herbort & Kunde, 2016). Second, the data pattern of Experiment 1 in which the full pointer was presented was rather similar to Experiment 2, where neither head nor body of the pointer was shown. Taken together, any effect of head orientations could be expected to be very small in our paradigm.

4. Conclusion

To sum up, we provide evidence that the interpretation of bent pointing gestures is mainly derived from the finger orientation. Additionally, the arm is affecting interpretations. Interpretations were generally biased away from the arm orientation (contrast effect). This suggests that the arm is processed as visual context and is not considered to carry directional information. Furthermore, the data revealed the straight pointing effect. That is, observers interpreted straight points more linearly than bent points. Potentially, the straight pointing effect appears as bent points are associated with higher uncertainty and thus considered less reliable.

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Declaration of competing interest

None.

Data availability

Data and analysis scripts are available at the Open Science Framework (https://osf.io/gbh3v/).

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Open science statement

Data and analysis scripts are available at the Open Science Framework (https://osf.io/gbh3v/).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.actpsy.2023.104062.

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