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RESEARCH ARTICLE

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Illusions as a tool to study the coding of pointing movements

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Abstract Pictorial illusions bias our judgments about certain visual attributes. Such illusions are therefore only expected to influence a task if these attributes are used to perform the task. When pointing to a position, different visual attributes could be used to guide the hand: direction and distance (or length) of the required displacement (vector coding) or the final position (position coding). In this study we used the Brentano illusion (an illusion of length) to determine which attributes are used in pointing. Several conditions were tested in which the visibility of the hand and the stimulus were varied. The illusion influenced movements between two points along the shaft of the figure, but not movements perpendicular to the shaft. When the hand and/or target were invisible during the movement, the influence of the illusion increased. Pointing movements under different visual conditions were based on different relative contributions of position and vector coding. The contribution of vector coding was always rather modest.

Keywords Illusion · Action · Perception · Coding · Human

Introduction

In Euclidean space, length is the distance between two positions. However, there is ample evidence that people process visual information about these spatial attributes independently (Gillam and Chambers 1985; Gillam 1998; Mack et al. 1985; Post and Welch 1996; Smeets et al. 2002). The Brentano illusion (Fig. 1), like other variants of the Müller-Lyer illusion, primarily influences judgments of length. Thus, a task will only be influenced by this illusion if the task requires a visual estimate of length.

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This reasoning can also be reversed. The illusion can be used to determine which attributes are used in pointing: the egocentric position of the endpoint (position coding: Bizzi et al. 1992; Carrazzo et al. 1999; Feldman and Levin 1995; McIntyre et al. 1997, 1998; Van den Dobbelsteen et al. 2001) or the distance and direction of the target relative to the starting position (vector coding: Bock and Eckmiller 1986; Desmurget et al. 1998; Messier and Kalaska 1997; Rossetti et al. 1995; Vindras and Viviani 1998). If an illusion that influences the perceived length of a line also influences the endpoints of movements along that line, we can conclude that the distance and direction of the required movement are used to help determine the endpoint. The magnitude of this influence (in particular under open-loop conditions) can help us to determine the relative roles of vector coding and of position coding in controlling our movements.

In the present study we use the Brentano illusion to determine the extent to which the distance and direction, rather than the egocentric position of the endpoint, contribute to the control of pointing movements. We know that the arrowheads of the Brentano illusion influence the judged length of the shaft. We assume that they have no effect on perceived positions (Post and Welch 1996) and directions (i.e., perpendicular alignment: Gillam and Chambers 1985). According to the vector coding hypothesis, when subjects point along the shaft from one arrowhead to another (Fig. 1) they will use the distorted information about the length of the shaft connecting the two arrowheads to guide their pointing movement. If the movement is made perpendicular to the shaft from a position outside the illusion, the shaft's (distorted) length is irrelevant. Thus, such pointing movements will not be influenced by the illusion. If the movement is made in any other direction, we expect intermediate values. In order to avoid making assumptions about how distances and directions outside the figure are influenced by the arrowheads, we will concentrate on pointing movements that are either along the shaft or perpendicular to the shaft of the Brentano figure.

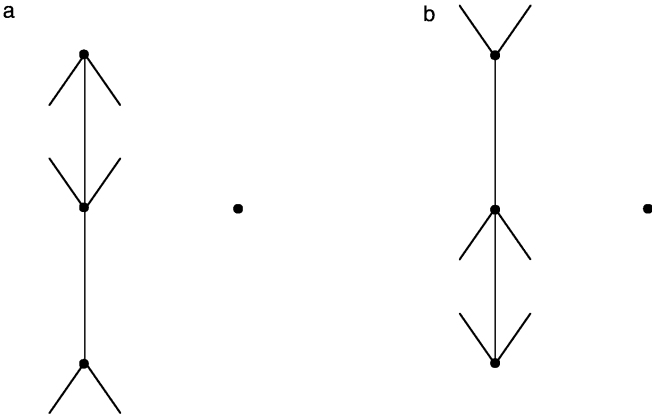


Fig. 1a, b The Brentano illusion with the wings-in configuration at the top (**a**) and with the wings-out configuration at the top (**b**). Each subject performed one block of trials for each configuration. The *dots* indicate the positions at which a target could appear (on one of the arrowheads or outside the illusion). Only one configuration was visible at a time

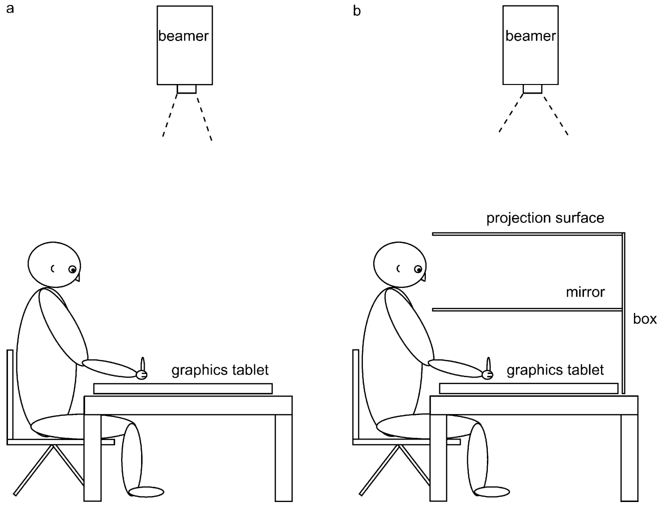


Fig. 2a, b A schematic view of the apparatus. **a** In the hand visible conditions, the stimulus was projected directly on the graphics tablet. **b** In the hand invisible conditions, subjects looked at the projected image via a mirror. They held the pen on the graphics tablet underneath the mirror. The task was always to bring the tip of the pen to the red target dot

According to the position coding hypothesis, there will be no influence of the illusion at all.

A factor that can influence the kind of information that is used, and with that whether the illusion will influence the task, is visibility of the hand and the stimulus. If subjects can see both the target and their hand, they will almost certainly detect initial errors and correct them during the movement (Abrams et al. 1990; Prablanc and Martin 1992). If the hand is not visible during the movement, subjects may be less certain about the position of the hand, and therefore find it harder to control its position. In such cases they are more likely to use length information to control the distance to be covered by their pointing movements. Similarly, if the end position is not visible, they are more likely to consider the previously seen length as the distance that they should move. If the information of both the hand and the target is removed, the likelihood to use length information will even be larger. Thus, the influence of the illusion is expected to increase as feedback is removed.

Materials and methods

Subjects

This study is part of an ongoing research program that has been approved by the local ethics committee. Thirteen right-handed colleagues volunteered to take part in the study after being informed about what they would be required to do. All had normal or corrected-to-normal vision.

Apparatus and stimulus

The stimulus consisted of a black Brentano figure and a red target dot on a white background (Fig. 1). The two vertical shafts each had a length of 8 cm. The length of the wings was 2.2 cm. The inclination of the wings with respect to the shafts was 30°. Two configurations of the Brentano illusion were used: one with the wings-in on top and one with the wings-out on top. The target dot (diameter 0.2 cm) could appear either on one of the three arrowheads of the Brentano illusion (top, middle or bottom) or outside the figure. The target outside the figure was presented 8 cm to the right of the middle arrowhead. In each trial the figure and only one target dot were presented.

The stimulus was projected directly on a graphics tablet (WACOM A2), or on the projection surface of a box that was placed on the graphics tablet (Fig. 2). In the latter case subjects could see the stimulus at the level of the tablet through a mirror without seeing their hand. The resolution of the projected image was 1024 by 768 pixels, with 1 pixel corresponding to about 0.5 mm. Pointing positions were registered as the positions at which the tip of the pen stopped moving on the graphics tablet. This was defined as the position at the first sample on which the tip of the pen had moved less than 1 mm during the preceding 300 ms. Positions were sampled at 200 Hz with an accuracy of about 0.25 mm.

Procedure

All subjects performed four conditions of a pointing task in random order in separate sessions. These conditions consisted of all possible combinations of the hand and target being visible or invisible during the movement (four possible combinations). Each condition contained two blocks of 400 trials, one for each configuration of the Brentano figure. The order of the blocks was counterbalanced across subjects. The subjects were asked to bring the tip of a pen to a red target dot, which was either on one of the three arrowheads or at a position outside the illusion (Fig. 1). The endpoint of one movement was the starting position of the pointing movement to the next target.

In the two stimulus visible conditions, the stimulus was continuously visible at the same location. When the subject stopped moving, the red target dot jumped to a new position. In the two stimulus invisible conditions, the stimulus was only visible before subjects started their pointing movement. As soon as subjects moved the pen, the stimulus disappeared from view. When the subject finished the pointing movement, the stimulus appeared again with the target dot at a new position.

In the two hand visible conditions, the image was projected onto the tablet, so that subjects saw their hand all the time. If the target disappeared once the subject started to move, the computer aligned the arrowhead to which the subject had just moved with the tip of the pen when the stimulus re-appeared, so that it seemed to the subjects as if they never made a mistake. If subjects drifted outside the range of the tablet, the stimulus reappeared at the middle of the tablet, and that trial was discarded. In the two conditions in which the hand was invisible, the stimulus was projected on a back-projection screen at the top of a box (Fig. 2). The box was placed on the graphics tablet. Subjects looked at the projected image via a mirror. They held the pen underneath the mirror. In this case there was no need to re-align the stimulus.

After completing the four conditions of the pointing task, subjects performed a length-matching task, in which they had to draw an invisible line of the same length as either the wings-in part or the wings-out part of the Brentano illusion. The line had to be drawn smoothly in one vertical stroke next to the illusion. The same stimulus as in the pointing task was projected directly on the graphics tablet. Instead of one red target dot, two red dots were presented. One red dot was always presented at the middle arrowhead and the other either at the arrowhead at the top or at the bottom of the figure. Subjects had to draw a straight line of the same length as the line between the target dots. They had to start at a red dot that was presented 10 cm to the right of the figure. In order to make sure that subjects could not align their drawing with elements of the figure, this dot was not aligned with either arrowhead, but 2.5–3.7 cm below the top or above the bottom arrowhead. If the upper part of the figure had to be matched, the starting dot was near the top arrowhead. Otherwise, it was near the bottom arrowhead. The drawing direction was always toward the middle arrowhead (from the top to the middle or from the bottom to the middle). When subjects started to move the pen, the figure and the starting dot disappeared from view but the hand remained visible. The trajectory of the drawing was recorded on the graphics tablet. This condition also contained two blocks of 400 trials, one block for each configuration of the Brentano figure.

After having analyzed the data, we asked subjects to perform two control pointing experiments, one with movement time instructions and the other with "direction of approach" instructions. The control experiment in which the movement time instruction (slow or fast) was varied was performed in the condition in which the hand was visible and the stimulus invisible. In the slow trials the movement time had to be between 900 and 1300 ms. In the fast trials it had to be between 450 and 650 ms. Trials were now blocked by instructions for the duration of the pointing movement. The configuration of the Brentano figure was randomized across trials (this was possible because the stimulus always disappeared). Auditory feedback was given on every trial that was not within the appropriate range of movement times. Trials with movement times outside the range were deleted from data analysis. Half the subjects performed the slow pointing movements before the fast ones.

The control experiment in which the "direction of approach" instruction was varied was performed in both conditions in which the stimulus was invisible during the movement (with and without visibility of the hand). The procedures in these conditions were identical to the corresponding original pointing conditions except that the target dot was always on one of the arrowheads. This means that movements were only made between the arrowheads. A beep sounded in 50% of the trials in which the target appeared at the central arrowhead. In those trials, the subjects' task was to draw a strongly curved path to the presented target. Otherwise, a straight path had to be drawn. A path was considered strongly curved when there was a deviation of 8–12 cm to the right of the shaft. A straight path had to be within a range of 2 cm to the left or right of the shaft. Auditory feedback was given for every path that was not drawn in accordance with the demands of the trial. These trials were excluded from data analysis.

Statistical analysis

The quantitative comparison of the influence of the illusion was based exclusively on the three types of movements toward the target dot on the middle arrowhead (upward, downward or leftward). In general, subjects tend to misjudge the distance that is to be moved when viewing of the hand and/or stimulus is prevented. Estimates of these distances differ between subjects and between different spatial positions; therefore, a measure of the magnitude of the illusion was computed for each subject, movement type and condition, which is independent of the amplitude of the pointing movement and which always compares the influence of the illusion at the same (average) spatial position.

For each type of movement we calculated the median vertical distance between the endpoints of pointing movements for the two configurations (wings-in on top, wings-out on top).[1] The difference in distance between configurations was divided by the median vertical distance between the pointing position for the top and bottom target to correct for general tendencies to overestimate or underestimate the extent (in particular when no feedback of the hand was provided). The result is the size of the illusion expressed as a percentage of the length of a shaft of the Brentano figure.

Statistical tests were all conducted across subjects. For each pointing condition a repeated measures ANOVA was performed on the illusion magnitudes to check whether the three types of pointing movements were influenced differently by the illusion. One-sample t-tests were performed to check whether the illusion magnitude in each of the three types of movements differed from zero (to check whether there is any effect of the illusion) and paired t-tests were used to determine which types of pointing movements differed. In the length-matching task, one-sample t-tests were conducted to check whether there was an effect of the illusion for each direction of drawing (from the top to the middle and from the bottom to the middle); a paired t-test was conducted to check whether the illusion differed between the directions of drawing.

Whether subjects used length information to the same extent in the four pointing conditions and in the length-matching task was tested with another repeated measures ANOVA. Since the magnitudes of the illusion for the upward and downward movements were not expected to differ, these magnitudes were averaged for this analysis. Pointing movements from outside perpendicular to the shaft were not expected to be influenced by the illusion at all and are therefore not considered in the comparison between conditions.

For the movement time condition, similar tests were conducted as for the original conditions. The movements between the arrowheads were combined to compare the fast and slow movements in a paired t-test. In the "direction of approach" conditions, a factorial ANOVA was performed to check for main effects (visibility condition and direction of approach) and for an interaction between the two factors.

Results

Figure 3 shows the lengths of the pointing movements for individual subjects, movement types (top to middle, bottom to middle), figure orientations (wings out at top or bottom) and conditions (visibility of the hand and stimulus, length matching). The figure shows that there are large deviations from the veridical distance (8 cm), especially when vision of the hand is blocked. These deviations are not necessarily related to the illusion. The effect of the illusion is evident from the fact that most points are below the unity line. The following figures present the data in a way that is insensitive to systematically over- or underestimating the distance (as described in the statistical analysis section).

[1]When the image was realigned in the hand visible and target invisible condition, the coordinate system for determining the positions was redefined so that positions are always in relation to the figure on the screen.

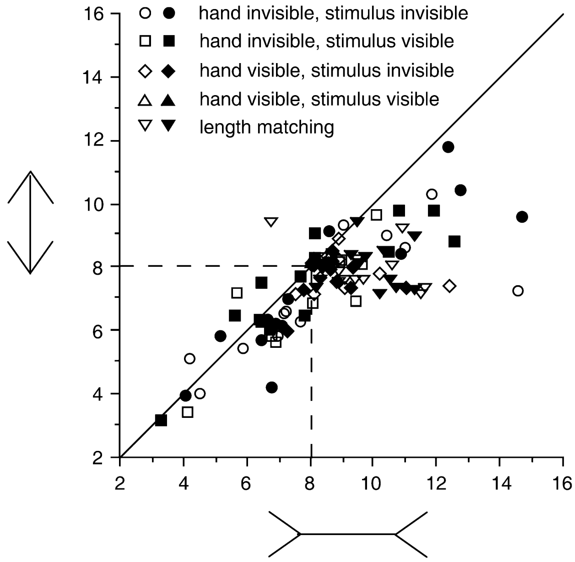
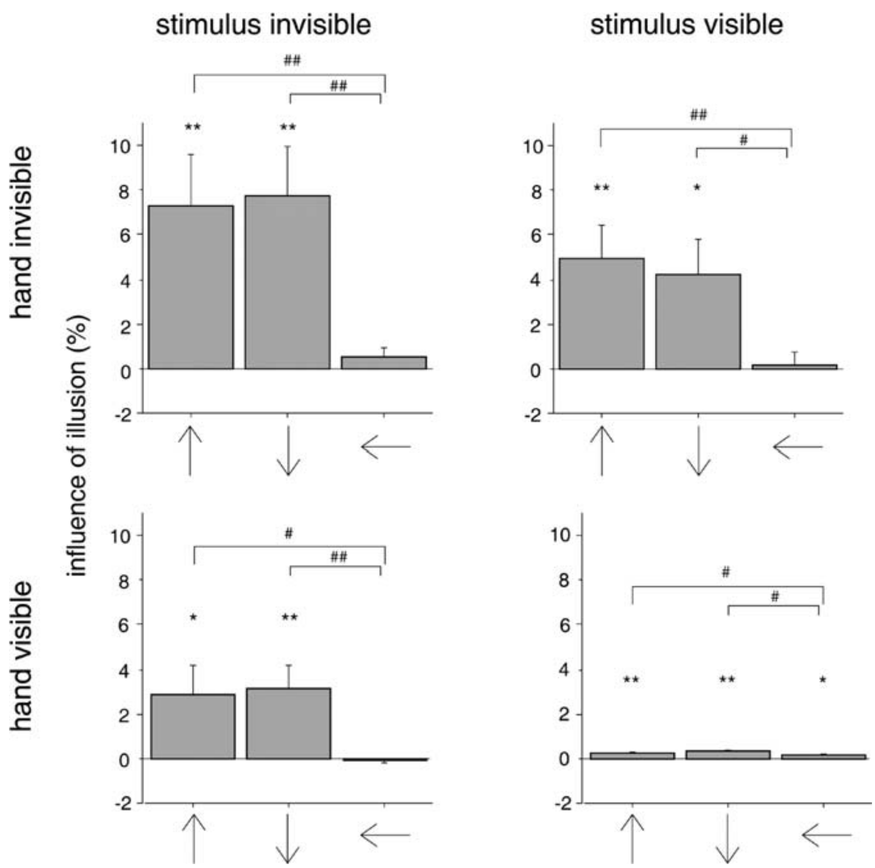


Fig. 3 Lengths of the pointing movements (pointing tasks) and of line drawings (length-matching task) for the "longer" and the "shorter" part of the shaft. *Open symbols* indicate that the shaft was on the bottom of the figure. *Closed symbols* indicate that the shaft was on top

The illusion influenced the final position of pointing movements that were along the shaft (between the arrowheads) in all four conditions (Fig. 4). The position was shifted by less than 1% of the length of the shaft in the full feedback condition, about 4% in the conditions with either feedback of the hand or of the target, and about 8% in the condition with no feedback. Movements perpendicular to the shaft showed no significant effect of the illusion, except in the condition where the hand and the stimulus were both visible. In that case the effect was extremely small, about 1/10 of the diameter of the red target. As the shift of the endpoints of movements perpendicular to the shaft in the other conditions did not differ significantly from this value, we regard this as our best estimate of the illusory effect on perceived position. The shift of endpoints of movements up and down the shaft was always larger than that of pointing movements from outside, perpendicular to the shaft (Fig. 4), and was equal for the two directions. These results confirm our assumption that the illusion influences the judged length of the line to a much larger extent than its endpoints.

In Fig. 4, we compared the use of length information in the movements toward the middle target dot, for which we designed the statistical analysis. For movements away from the middle target dot, we expect a similar use of length information. Indeed, the latter movements showed an equal amount of illusion as movements toward the middle target dot. For movements from outside the illusion diagonally to the top or bottom target (and vice versa), we expect less use of length information than for movements within the illusory figure, but such an influence cannot be excluded altogether. Figure 5 shows that there was indeed a smaller influence.

Fig. 4 Illusion magnitudes for the three types of movements toward the middle target dot in each condition of the main pointing experiment. *Asterisks* indicate a significant effect of the illusion (* p<0.05; ** p<0.01). Significant differences between the types of movement are also shown (# p<0.05; ## p<0.01). Error bars represent standard errors between subjects



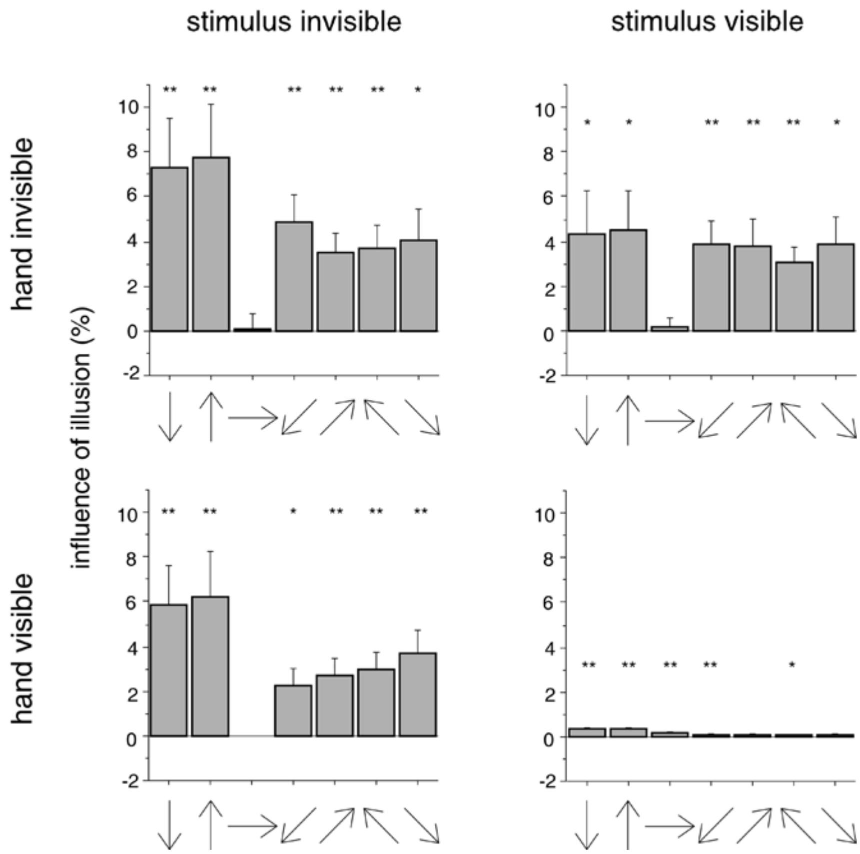


Fig. 5 Illusion magnitudes for all the other movements in each condition of the main pointing experiment. *Asterisks* indicate a significant effect of the illusion (* p<0.05; ** p<0.01). Error bars represent standard errors between subjects

To better understand what kind of information is used in these four pointing tasks, we compared the results with those of the length-matching task. An illusion magnitude of about 23% was found irrespective of the drawing direction (upward or downward). This is the amount by which the illusion affects length information. The influence of the illusion in the length-matching task was much larger than in any of the pointing conditions (Fig. 6), indicating that length information has a rather modest contribution to the final position of a pointing movement (less than 32%).

The difference in effect of the illusion between the conditions could have been caused by differences in movement time. When moving slowly, better control and adjustment of the arm movement is possible, so subjects may make more use of position information in that case. We therefore performed a control experiment with two different instructions about movement speed. The illusion influenced movement endpoints of fast (average movement time: 539 ms) and slow (average movement time: 1,021 ms) movements to a similar extent (Fig. 7a). The movement times were not affected by the illusion (p>0.05). Movement speed does not change the influence of the illusion.

The difference in effect of the illusion between the different movement types (along the shaft, perpendicular to the shaft) could have been caused by the direction in which the hand approaches the target: perpendicular to the shaft for movements from outside and parallel with the shaft for movements between the arrowheads. To examine

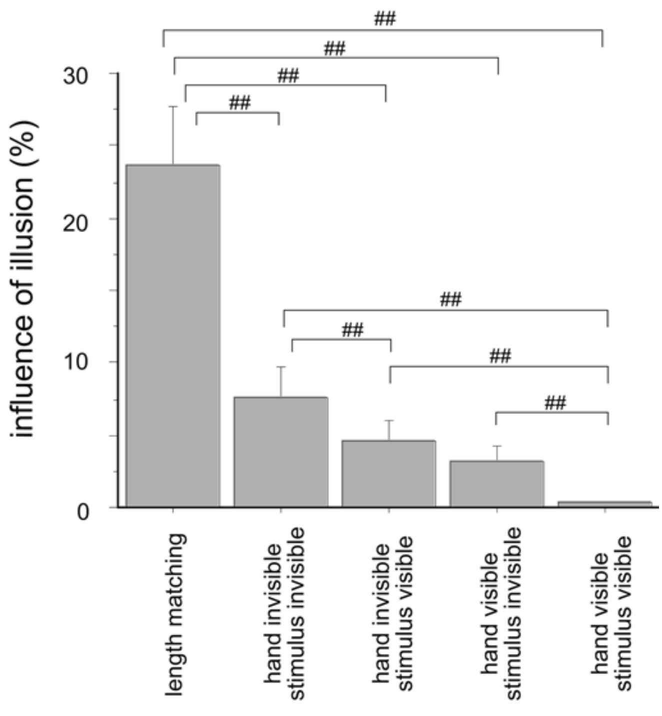
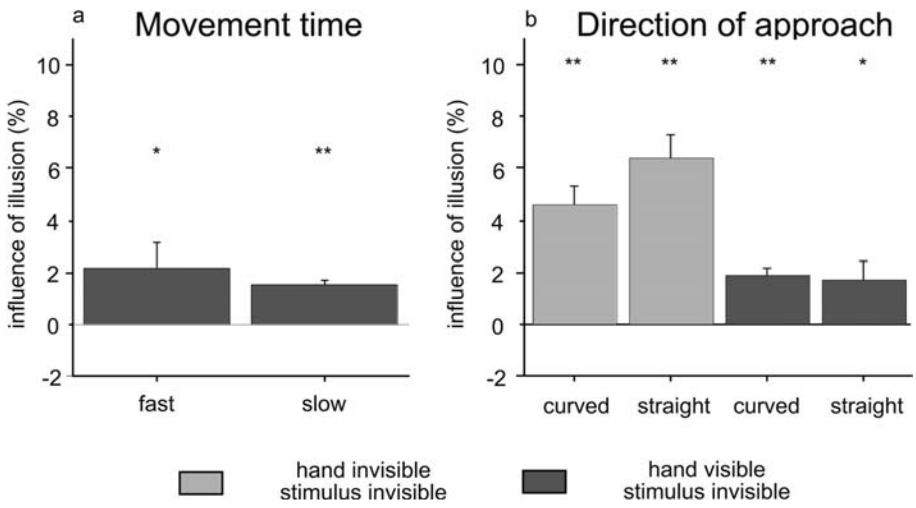


Fig. 6 Average influence of the illusion for the two movements along the shaft in each condition of the main pointing experiment and in the length-matching task. Significant differences between the conditions are indicated (## p<0.01). Error bars represent standard errors between subjects

Fig. 7a, b The results of the two control experiments. **a** Illusion magnitudes did not differ between fast and slow movements. *Asterisks* indicate a significant effect of the illusion (*p<0.05; **p<0.01). Error bars represent standard errors between subjects. **b** Illusion magnitudes did not differ between curved and straight movements (n.s.: p>0.05). *Asterisks* indicate a significant effect of the illusion (*p<0.05; **p<0.01)



this possibility, subjects performed another control experiment in which the direction of approach was varied. The illusion influenced the curved and the straight movements to the same extent in both visibility conditions (Fig. 7b). As expected from our main experiment, the effect of the illusion differed between the two conditions. There was no interaction between the visibility conditions and the direction of approach. Thus, the way an arm movement is executed does not determine whether position coding or vector coding is used.

Discussion

All pointing movements along the shaft were influenced by the illusion. For movements that were perpendicular to the shaft, the illusion only had a very small effect, which only reached significance when the hand and the stimulus were both visible. The magnitude of this bias was about ten times smaller than the diameter of the target dot. We interpret this as an effect on the perceived position. This effect is very small (0.3%) in comparison with that on perceived length (23%).

Our results can explain a discrepancy between previous studies on pointing to an arrowhead of the Müller-Lyer illusion (Gentilucci et al. 1996; Mack et al. 1985; Post and Welch 1996). In these studies the task was to point to an arrowhead from a starting position outside the figure. In the studies of Mack et al. (1985) and Post and Welch (1996) the pointing movements were made more or less orthogonal to the shaft, which made illusory shaft length irrelevant. As we would expect, these studies did not find an effect of the illusion. In the study of Gentilucci et al. (1996), the pointing movements started outside the figure, but they were largely along the shaft, so that its illusory length could be relevant. We are therefore not surprised that in the latter study the illusion did affect pointing. Gentilucci et al. (1996) ascribed the difference in results to the orientation of the illusion: horizontal in the former two studies and vertical in the latter. Our results suggest that it is the relationship between the starting point of the movement and the orientation of the figure that determines whether the illusion has an effect.

It is well established that the task that is used to evaluate the magnitude of an illusion can influence the result. In an earlier study (de Grave et al. 2002) we showed that even for a single perceptual task the influence of an illusion (the Roelofs effect) could depend on seemingly irrelevant factors. In this study we show that the starting position of the hand influences where one points when asked to indicate the vertices of an illusory figure (the Brentano illusion). Thus, the influence of illusions probably tells us more about the kind of information that is used than about what it is used for.

The planning and control model of Glover and Dixon (Glover and Dixon 2001, 2002) states that the planning of the movement is influenced by the illusion, but errors in planning are corrected during on-line control of the movement. This is consistent with our finding that the influence of the illusion is largest when there is least possibility to correct the movement. However, this model predicts an influence of the movement time. If subjects make fast pointing movements there is little time to make on-line corrections and therefore the influence of the illusion should be larger. The model also predicts that the movement time depends on the perceptual length of the shaft. If a movement is planned in advance for a distance that seems shorter than it actually is (movement along the "short" shaft), the end position will not have been reached by the time the planned movement time has passed. To reach the end point, a longer movement must be made. Thus, the movement time for the shaft that looks shorter should be longer than that for the shaft that looks longer.

To test these hypotheses we performed a control pointing experiment in which movement time instructions (slow or fast) were varied. We found no difference in the effect of the illusion between fast and slow movements. We also found no differences in movement time between the shaft that looks long and the shaft that looks short. Thus, this model alone cannot explain our data.

The results cannot be interpreted as either pure position coding or pure vector coding. For pure position coding, one would have to conclude that the perceived egocentric endpoint depends on the starting point of the hand (within or outside the figure). For pure vector coding, one would have to conclude that on-line control reduces the influence of initial errors caused by relying on judged length. However, as mentioned above, if on-line control reduces an initial error, the fast movements in our experiment should have shown a much larger effect of the illusion than the slow movements, which they did not. Thus, the endpoints of pointing movements show effects of both position coding and vector coding.

In the length-matching task, subjects directly reported the perceived length; therefore, we assume that the magnitude of the illusion found in this task (about 23%) is the maximum that could be expected in the pointing tasks. In all pointing conditions, the magnitude of the illusion was much smaller (≤7.8%), which means that subjects never only used length information. They did not even do so when no visual feedback was provided during the movement. We conclude that length information probably normally plays a very minor role in determining the endpoint of a movement.

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