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RESEARCH ARTICLE

Impact of action planning on visual and body perception in a virtual grasping task

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Abstract

The present study examined mutual influences of visual and body-related signals during planning of an object-oriented action. Participants were to enclose a visual target object using two cursors controlled by the movements of their fingers. During movement preparation, they were asked to judge either the size of the object or a certain finger distance. Both types of judgments were systematically affected by the transformation of finger movements into the movements of visual cursors. We suggest that these biases are perceptual consequences of sensory integration of visual and body-related signals relating to the same external object.

Keywords Perception and action planning · Multisensory integration · Action-specific perception · Visual perception · Body perception

Introduction

Previous research has provided several examples for perceptual changes in the context of goal-directed actions. Two sorts of observations are of a particular relevance for the present study. First, experimentally manipulating certain features of the body or its movement proved to affect the visual perception of external objects to which potential or real actions were related (e.g., Bhalla and Proffitt 1999; Witt and Sugovic 2012; for reviews, see, e.g., Philbeck and Witt 2015; Proffitt and Linkenauger 2013; Witt 2011a). For example, when humans are provided with a tool extending the effective arm length to manipulate a distant object the egocentric distance to that object is judged as smaller than without the tool (Davoli et al. 2012; Witt 2011b; Witt and Proffitt 2008; Witt et al. 2005). Second, conceptually similar manipulations also proved to affect the perception of the body or its movement (e.g., Cardinali et al. 2009; Ladwig et al. 2012; Rand and Heuer 2013, 2016; Sposito et al. 2012; Sutter et al. 2008). For example, when a spatial mismatch between a movement of the hand and the movement of the cursor controlled by the hand is introduced participants usually misperceive the hand in the direction of the cursor (e.g., Sutter et al. 2008).

In spite of their diversity, these studies share some common features. In particular, participants usually see and manipulate a certain external object. Thus, visual and body-related (tactile, proprioceptive) signals can be considered as redundant in that both provide information about the same environmental object or event. Moreover, the experimenter typically introduces a discrepancy between these signals, i.e., a type of crossmodal conflict and studies the impact of this manipulation. The traditional multisensory research suggests that redundant sensory signals are integrated in a statistically optimal fashion taking signal reliability into account (e.g., Ernst 2006; Ernst and Bülthoff 2004). Moreover, this research also predicts mutual perceptual biases when the integrated signals provided divergent information about an object or event.[1] Thus, changes in object and body

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[1] Consider, e.g., a well-studied action of manual grasping an object (Ernst and Banks 2002). In this case, information about the size of the object is provided by the hand as well as by the eyes. When the size provided by the haptics deviates from the visual size the perceived size of the object is in-between the unimodal percepts. That is, what is visually sensed is attracted by what is bodily felt and, vice versa, the haptic impression is biased towards the visual information.

perception in the context of goal-directed actions might be closely related to the basic principles of sensory integration of multimodal signals (Kirsch et al. 2017; cf. also Debats et al. 2017a and Philbeck and Witt 2015).

To corroborate this idea, we recently introduced a paradigm that contains common characteristics of experiments testing for perceptual changes accompanied body-related manipulations as well as of traditional multisensory setups (Kirsch et al. 2017). Participants repeatedly enclosed a distant object by a pair of visual cursors controlled by the movements of the index finger and thumb and judged either the size of the object or the actual distance between the fingers. The judged object size was attracted by the current finger distance, and vice versa, the judged finger distance was attracted by the current object's size. This result indicated sensory integration of visual and body-related signals in spite of a clear spatial separation of their origin. In a follow-up study, we showed that the magnitude of these biases varies as a function of visual signal reliability and of causal inference processes (Kirsch and Kunde 2019).

These results are well in line with a multisensory view of perceptual biases observed in manifold action contexts. However, given the high diversity of the studied phenomena and the used paradigms, this approach requires further investigation. Specifically, actions impact visual object perception already during action planning, that is, before action execution (e.g., Kirsch and Kunde 2013; Müsseler and Hommel 1997; Lindemann and Bekkering 2009). In such a situation, no body-related afferent input is yet available which could inform about an external object at the time of its visual appearance. Thus, it is not obvious how the assumed integration of multimodal signals might work here.

We argue, however, that multimodal integration can and should work also during action planning. This is possible, because planning a goal-directed body movement involves the activation of representations of interoceptive as well as exteroceptive consequences of that movement. Such effect representations might mediate the selection of a body movement itself, as suggested by the so-called idemotor approach of action control (e.g., Elsner and Hommel 2001; Kunde 2001; for a review, see, e.g., Shin et al. 2010), or they are predicted based on peripheral motor commands as suggested by the idea of internal forward models (e.g., Wolpert et al. 1995). Following both approaches, thus, predictable re-afferent body-related input of efferent activity should be available during planning that efferent activity. If so, then this information can be combined, at least in theory, with information received through other senses to improve the overall percept of an external object.

This reasoning gives rise to more precise predictions regarding perceptual biases during action planning beyond the prediction that action planning should generally impact object perception. Following sensory integration, the visual information of the object should also affect body perception. The present study was conducted to test this claim. Three experiments are reported below in which we measured the perception of visually presented objects and of body states before object-related actions were executed. To anticipate the results, we observed a mutual influence of visual and haptic information during action planning as predicted.

Experiment 1

In Experiment 1, we adapted the previously used paradigm of virtual grasping to the question of interest as follows (see Fig. 1; cf. also Kirsch et al. 2017). At the beginning of each trial, a movement cue was presented. This cue informed the participants about the current transformation of their finger movements into the movements of a pair of virtual cursors (i.e., gain). Then, a target object (square) was shortly presented. Following the target disappearance, participants were asked to estimate either the size of the target or the finger distance required for grabbing the target by adjusting a pair of visual markers. Then, they actually tried to grab the remembered object by moving their fingers inserted in a finger movement device (without visual feedback). Finally, feedback about movement accuracy was given in that the target object reappeared together with a pair of movement cursors. The distance between the cursors corresponded to the final finger distance transformed according to the gain factor which the participants were informed of at the beginning of the trial.

The general rationale was as follows. The movement cue and the target will trigger action-planning processes which involve anticipation of the final finger distance. This anticipated body-related input and the visual object size will then be integrated to improve the object's mental representation. One consequence of this process is a mutual perceptual attraction between visual object's size and bodily sensed finger distance. That is, the perceived visual size of the object will be attracted towards the planned finger distance, whereas the planned finger distance will be perceptually attracted towards the visual object's size (see Fig. 2, left part). Both perceptual biases should be expressed in the implemented judgment procedures, however, not in the same way.

For the estimates of object's size, the reasoning is straightforward: participants will adjust the visual markers to the perceived size of the object. Accordingly, an

Footnote 1 (continued)

This is assumed to be a consequence of sensory integration aiming at a robust percept given noise in sensory systems.

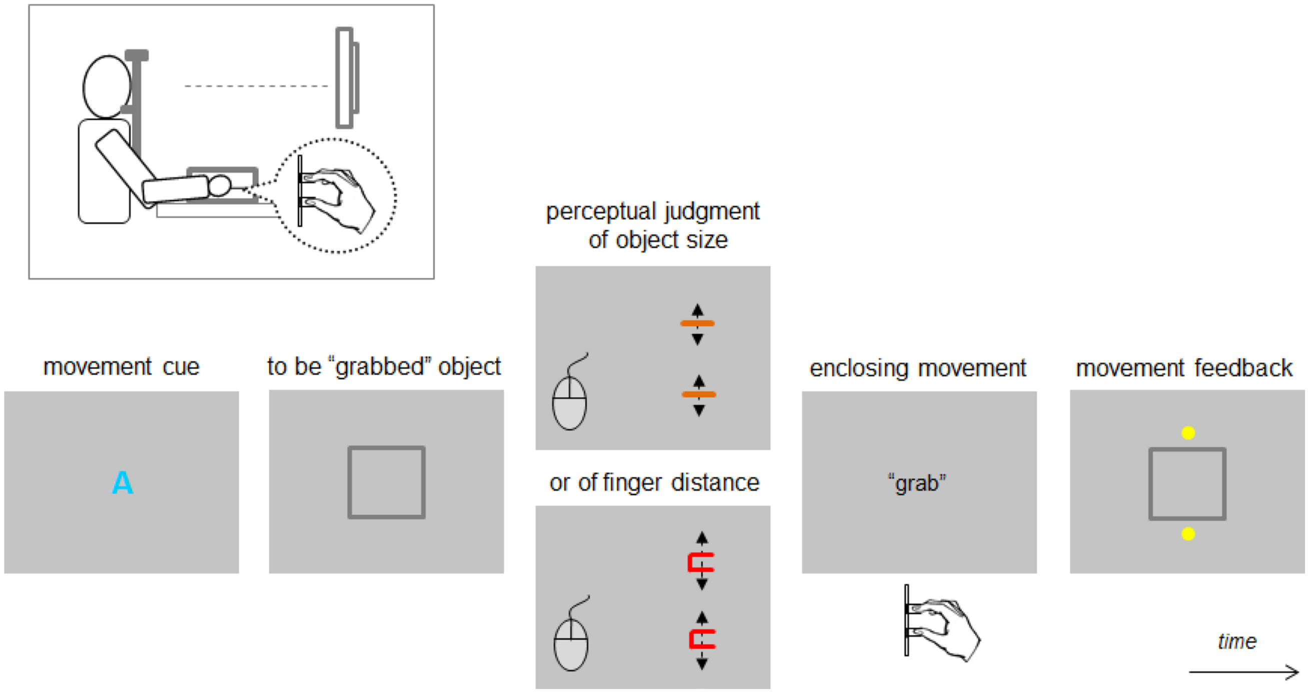

Fig. 1 Main trial events in Experiment 1. Superimposed is the experimental setup (upper left part). After being informed about the current mapping between the cursors and finger movements by a cue, the participants saw a square which has to be virtually grabbed after either its size or the final finger distance was judged. At the end of each trial feedback about movement, accuracy was provided

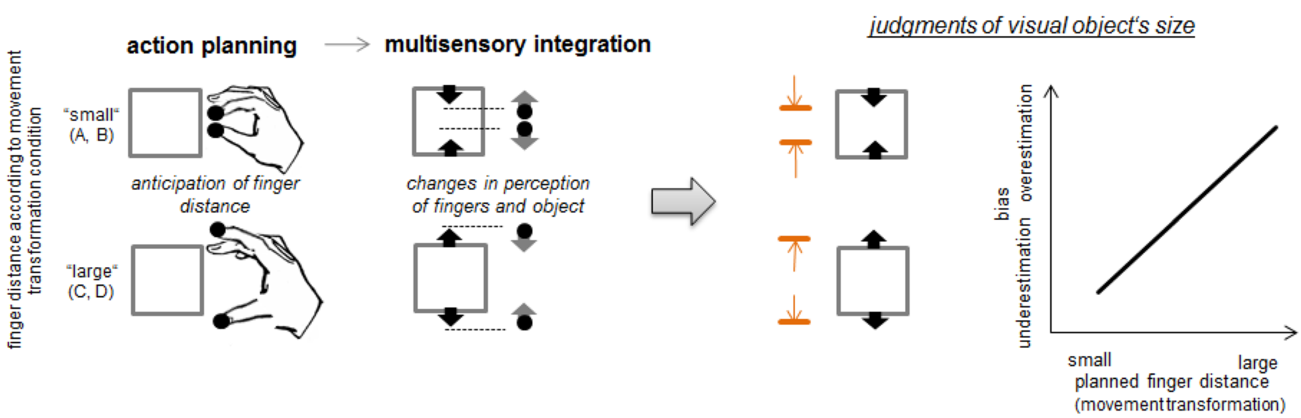

Fig. 2 Main hypothesis regarding the involved processes and the prediction for the object judgments in Experiment 1. Left part: the presentation of the square was assumed to trigger motor planning processes including anticipation of the final finger distance. The planned finger distance was then expected to be combined with the visual object size (multisensory integration). As a result, the visual object size should be attracted by the planned finger distance, and vice versa, the perception of the planned finger distance should be attracted by the current visual object's size. The right part of the figure illustrates how changes in perceived object's size should be captured by the used visual judgment method. Orange lines are visual markers adjusted to the perceived height of the square

increase in perceived object's size should result in an increase in the adjusted distance between the visual markers. Following action planning and sensory integration of visual object size and the anticipated final finger distance, an increase in planned finger distance required to grab an object should increase size estimates of this object (see Fig. 2, right part).

Matters are more complicated for the finger judgments. Because perceptual judgement and action planning utilize, at least to some extent, separate cognitive and neuronal resources (e.g., Goodale and Milner 1992), the judgment of finger distance will likely be derived from mentally simulating the required action again. Moreover, asking the participants to adjust the visual markers to how far the fingers

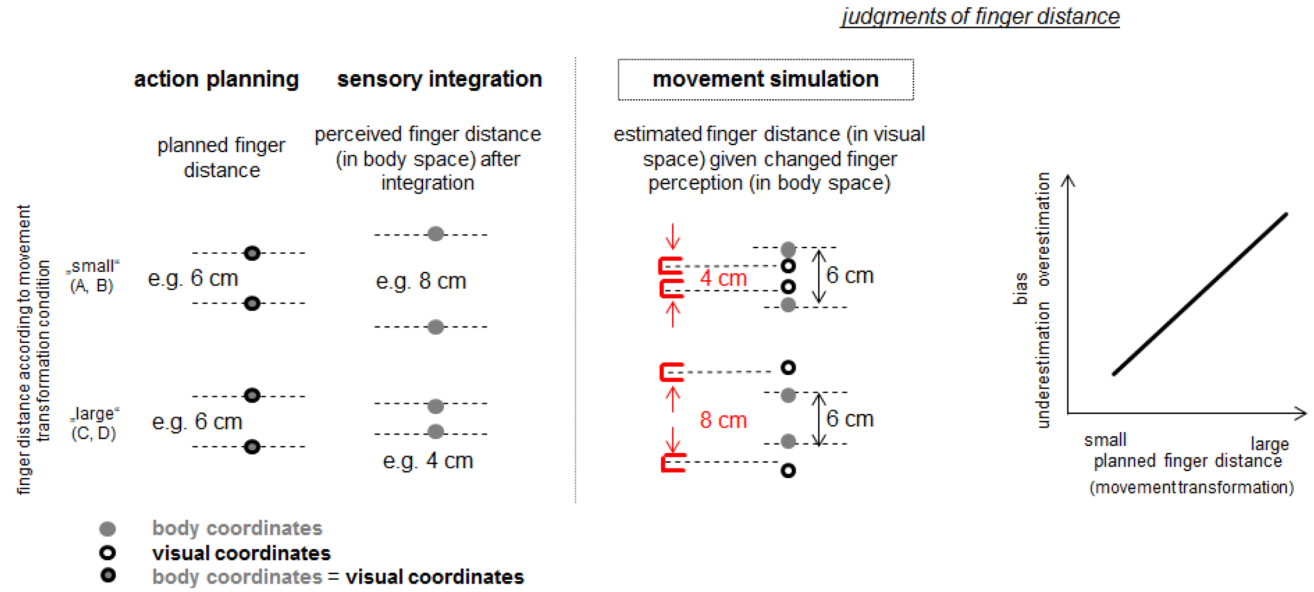

Fig. 3 This figure illustrates how changes in perceived finger distance following action planning and multisensory integration should be captured by the employed visual judgment method. Two hypothetical examples are presented, where a finger distance of 6 cm is planned. In case of small distances, where the planned finger distance is smaller than the size of the target object, the bodily sensed finger distance after multisensory integration is larger than it really (or visually) is (e.g., 8 cm). During the judgment procedure, the originally planned distance (of 6 cm) will be simulated or imagined. Given changes in finger perception, this will now result in an adjustment of visual markers to 4 cm (i.e., to a visual finger distance which corresponds to the felt distance of 6 cm). In contrast, when the planned finger distance is larger than the size of the target object ("large" distances), this distance should be overestimated

will be apart requires the transformation of the final finger distance into visual coordinates.

Now, consider that a participant plans to grab a certain target object by an objective finger distance of, e.g., 6 cm after she was informed about movement transformation and the size of the target object (see Fig. 3). This distance can be assumed to be subjectively equivalent in visual as well as in body space before sensory integration. However, after sensory integration, the felt finger distance does no longer match the visual distance, and may now amount to, e.g., 4 cm. When then asked how the originally planned distance of 6 cm should visually look like during the judgment procedure, the participants will probably adjust the visual markers to a distance, where they (bodily) feel the originally planned distance of 6 cm, which after integration corresponds to a visual distance between the markers of, e.g., 8 cm. Thus, a judged finger distance can be assumed to be overestimated with the present procedure when this distance is perceived as smaller in body-related space than in visual space following sensory integration. This should apply to planning of larger finger distances. In contrast, a judged finger distance can be assumed to be underestimated when this distance is perceived as larger in body-related space. This should apply to planning of smaller finger distances.

More formally, the judgment procedure requires a matching of a subjective visual finger distance, S_{visual}, to a measurable distance between visual markers. During multisensory integration, the implemented movement transformation will affect the mapping[2] between subjective visual distances, S_{visual}, and subjective body-related finger distances, S_{body}, so that $S_{\text{body}} > S_{\text{visual}}$ for the planning of smaller finger distances and $S_{\text{body}} < S_{\text{visual}}$ for the planning of larger finger distances (cf. Figs. 2 and 3, left parts). During the judgment procedure, S_{body} is adjusted to the originally planned finger distance (with $S'_{\text{visual}} = S'_{\text{body}}$) and S_{visual} is derived according to the current mapping between S_{body} and S_{visual}. By definition, a perceptual bias is the difference between the marked visual distance, i.e., S_{visual} and the objective finger distance during grabbing O_{body}. O_{body} can be considered as an index of the originally planned finger distance (S'_{visual}, S'_{body}) as well as of S_{body} during the judgment procedure (because S_{body} is assumed to be adjusted to the originally planned finger distance in the course of motor simulation as mentioned). The perceptual bias thus basically assessed the difference between S_{body} and S_{visual} by $S_{\text{visual}}–S_{\text{body}}$. Accordingly, negative bias values are expected for the planning of smaller and positive values for the planning of larger finger distances (cf. Fig. 3, right part). In other words, the predicted perceptual attraction of the planned finger distance by the object size should be expressed in an increase (rather than

[2] We return to this point in Experiment 3.

in a decrease) of overestimation with an increase in planned finger distance. We approved this rationale by testing the main hypothesis using a different methodical approach in Experiment 3.

In sum, participants' behavior in the present task can basically be explained by two processes. First, after being informed about movement transformation and target size, a finger distance is planned and multisensory integration takes place. This process is directly captured by the judgment of the target object. Second, when an estimate of finger distance is required, the participant is prompted to simulate the final finger distance in visual space based on a changed body perception.

Methods

Compliance with ethical standards

The experiments reported in this article have been performed in accordance with the Declaration of Helsinki (1964) and have been approved by the local ethics committee (GZ 2019-04). All participants gave their written informed consent for the procedures. The authors declare that they have no conflict of interest.

Participants

Twenty-four participants participated in Experiment 1. All were right-handed handed and naive to the purpose of the experiment. The sample included 16 females and 8 males (M_{age} = 28, SD = 8). The participants received monetary compensation or course credit for their participation. The sample size was determined a priori based on prior related work (see, e.g., Kirsch and Kunde 2013).

Apparatus

The main apparatus included a 19′ monitor (Fujitsu Siemens P19-1) and a finger movement device (see Fig. 1). The monitor was placed in front of the participants, so that the center of it was approximately at the eye level. The resolution of the monitor was set to 1280 × 1024 pixels (1 pixel = 0.294 mm) and its refresh rate was 60 Hz. All stimuli were presented on a gray background. The finger movement device was on a table. Participants used their right hand to manipulate it. The index finger and the thumb were placed on two U-shaped metal plates which were mirror-symmetrically interlocked. Participants were seated in a dimly lit experimental room at a distance of approximately 68 cm from the screen. Their head was supported by a combined chin-and-forehead rest.

Stimuli and procedure

Each trial started with a pair of dark-gray arrows (5 × 0.3 mm) presented in the middle of the screen (one upon the other with arrowheads oriented to each other). This stimulus required the participants to move the fingers inserted into the finger movement device to each other to initiate a next trial. As soon as the plates touched each other, a letter (A, B, C, or D; in cyan; 6 mm in size) appeared in the middle of the screen for 1000 ms. The letter indicated the current relation between the finger movements and the virtual movements of the cursors during virtual object grabbing (see also "Design"). The letter was followed by a fixation cross (light gray; 4 × 4 mm) that was presented for 1000 ms. Then, a dark-gray square (with line width of 0.3 mm) was shown for 100 ms in the middle of the screen.

Afterwards, either the height of the square or the finger distance required for the virtual grabbing of the square was judged. For this purpose, either a pair of orange lines (6 × 0.6 mm) or of red U-shaped objects (6 × 10 × 0.6 mm) appeared at the left or right part of the screen (ca 7/9 cm in respect to the center). In addition, at the upper middle part of the display, the German words for height ("Hoehe") and finger ("Finger") were presented (same color as for visual markers). Participants adjusted the distance between the visual markers by pressing mouse buttons of a computer mouse with the left hand. The left/right button increased/decreased the distance and the middle mouse button (scroll wheel) confirmed the estimate. The initial distance between the lines/objects randomly varied between 50 and 150% of the height of the square/of the required finger distance. When participants changed the fingers' posture of their right hand during the judgments, or when the middle mouse button was pressed without changing the initial distance of visual markers, an error feedback was presented and the trial was repeated.

After the estimate was confirmed, a German word for "grab" ("Greife") appeared. This was a signal to grab the square by visual movement cursors (presented subsequently), i.e., to place the fingers, so that movement cursors approach as much as possible the horizontal edges of the square. The participants had to press the middle mouse button when they reached the desired finger distance. Then, a feedback about movement accuracy was given for 500 ms. In particular, the previously shown square reappeared together with two circles (3 mm in diameter) which served as movement cursors and which were vertically aligned with the center of the square. The distance between the circles corresponded to the distance between the fingers transformed according to the current letter (i.e., to the current gain). When the circles touched the edges of the square, a clicking noise was presented though earphones and the circles were shown in green. Otherwise, the circles were yellow.

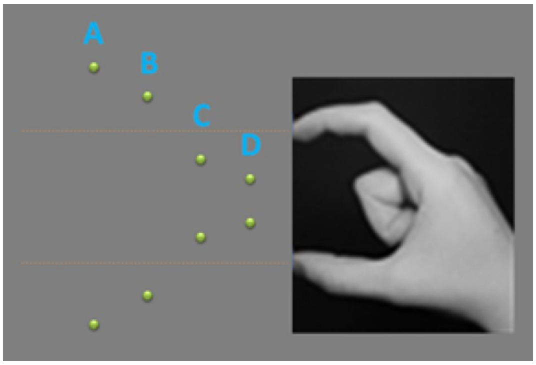

Fig. 4 This picture was a part of instructions and illustrates the rough distances between the cursors relative to a finger distance depending on movement transformation condition

Design

The finger distance was transformed to the cursor distance, so that the finger distance amounted to 0.4, 0.7, 1.3, or 1.6 of the distance between the cursors. That is the actual finger distance was multiplied by the gain factor of 2.5 (= 1/0.4), 1.4 (= 1/0.7), 0.7 (= 1/1.3), or 0.6 (= 1/1.6). As a result, the exact grabbing of a given square was associated with finger distances which amounted to 40, 70, 130, or 160% of the square's height. These gain conditions were assigned to the letters “A”, “B”, “C”, and “D”, respectively (cf. also Fig. 2). Note that we present the finger distance to cursor distance ratios in the results section when we refer to this gain manipulation. We believe that there values are easier to understand and are more informative under the present conditions than the applied gain factors. In addition to the manipulation of movement transformation, the square could be rather small (3.7 cm × 3.7 cm) or rather large (4.3 cm × 4.3 cm). In addition, either the height of the square or a finger distance was judged as mentioned earlier. Thus, there were three experimental factors [movement transformation (4 levels), square (2 levels), and type of judgment (2 levels)] resulting in 16 experimental conditions. The main experiment included 5 blocks of 64 trials each (4 repetitions of each condition in each block). The order of conditions was random.

At the beginning of the experiment, participants received detailed written and verbal instructions about the task including information about the different movement transformation conditions. This information was also provided by a picture indicating the rough distances between the cursors relative to a finger distance (see Fig. 4). The participants were asked to learn about the exact relation between their finger movements and the cursors in the course of the experiment. Before the main experiment started, a practice block including 24 trials was performed. The stimuli and procedure of the practice block were the same as in the main experiment. This initial block included 12 finger judgments, 12 square judgments, 12 small squares, 12 large squares, and 6 repetitions of each movement transformation condition (random order). The experimenter was present in the lab until the practice block was finished and the participants had the possibility to clarify task-related questions up to that time. This initial practice block was not included in the main analyses.

The practice block was followed by a first regular block. Because the task (esp. grabbing and finger judgment) was rather difficult, we expected learning-dependent changes in motor performance and judgment behavior to be continued after the practice block. Although not critical, such changes could complicate possible conclusions. We thus aimed to access the perceptual biases after a certain level of automaticity in task performance was achieved. Therefore, the first regular block was a priori considered as learning block and was also not included in the main analyses.

Data preprocessing

Prior to analyses, we checked whether the participants were able and/or willing to follow the task instructions and to learn the relation between their finger movements and the cursors. For this purpose, we screened the estimated distances and the finger distances adopted during grabbing for possible violations. A first indictor of such violations is present when the finger distance adopted during grabbing does not change with movement transformation condition (i.e., when the same finger distance is produced regardless of the letter identity). In a similar vein, when the estimates of the final finger distance do not increase with movement transformation condition, then either the instruction was misunderstood or the participant was not able or willing to follow it. During this screening procedure performed on the data of the main blocks of trials, we observed that two participants hardly changed their finger posture during grabbing depending on the four movement transformation conditions (see upper part of Fig. S1 in the supplementary materials). Moreover, in six participants (including one of the already mentioned), the judged finger distance did not vary with movement transformation, indicating that they judged the square in all trials (see lower part of Fig. S1 in the supplementary materials). Another participant obviously judged the finger distance in all trails using a reversed assignment of the movement transformation conditions to the letters (see lower part of Fig. S1 in the supplementary materials). Based on this, the data of three and eight participants were excluded from the analyses of square and finger judgments, respectively. This preprocessing thus ensured that the participants were only included in the analyses when they learned the correspondence between their fingers and the cursors depending on the movement transformation condition, at least to a certain degree.

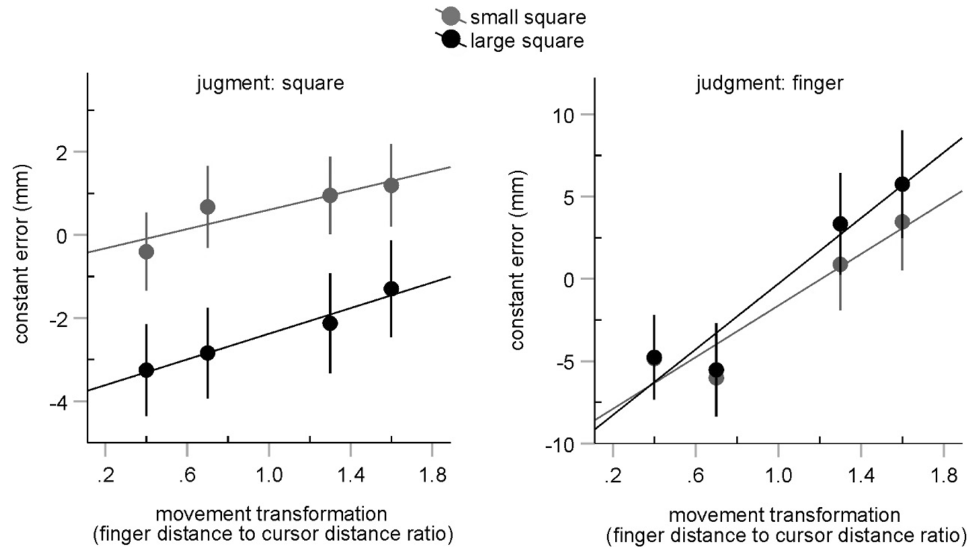

Fig. 5 Main results of Experiment 1. Error bars are standard errors (between-participants). Positive constant error values reflect overestimation, negative values indicate underestimation

A difference between the estimated feature and the real feature was computed for each trial. That is, for finger judgments, we subtracted the real finger distance adopted during grabbing the square from the estimated finger distance. Analogously, for square judgments, the real square height was subtracted from its estimate. Positive values reflect systematic overestimation, and negative values indicate underestimation. This measure, which we refer to as "constant error" hereafter, entered analyses of variance (ANOVA) which were performed for finger and square judgments separately.

The raw data of all experiments presented in this manuscript have been made publicly available (https://osf.io/ctp5f/).

Results

Square judgments

An ANOVA including movement transformation and square size as within-subjects factors and constant error in square judgments as a dependent variable revealed significant main effects of movement transformation, $F(3, 60) = 4.10$, $p = 0.010$, $\eta_p^2 = 0.170$, and square size, $F(1, 20) = 40.11$, $p < 0.001$, $\eta_p^2 = 0.667$, and a significant interaction of both, $F(3, 60) = 3.49$, $p = 0.021$, $\eta_p^2 = 0.148$. The larger square was associated with a more negative error than the smaller square (see left part of Fig. 5 for means). More importantly, an increase in the finger distance to cursor distance ratio caused an approximately linear increase in size estimates as expected [$F(1, 20) = 5.16$, $p = 0.034$, $\eta_p^2 = 0.205$ for a linear contrast]. We also analyzed each square size separately. In each analysis (ANOVA), the main effect of movement transformation was significant, $F(3, 60) = 3.20$, $p = 0.030$, $\eta_p^2 = 0.138$, and $F(3, 60) = 4.92$, $p = 0.004$, $\eta_p^2 = 0.197$, for the smaller and larger squares, respectively.

Finger judgments

An ANOVA including movement transformation and square size as within-subjects factors revealed significant main effects of movement transformation, $F(3, 45) = 10.00$, $p < 0.001$, $\eta_p^2 = 0.400$, and square size, $F(1, 15) = 4.90$, $p = 0.043$, $\eta_p^2 = 0.246$. The interaction was not significant, $F(3, 45) = 2.42$, $p = 0.078$, $\eta_p^2 = 0.139$. The judged finger distance tended to increase with an increase in square size (see right part of Fig. 5 for means). More importantly, an increase in the finger distance to cursor distance ratio increased the constant judgement error [$F(1, 15) = 10.55$, $p = 0.005$, $\eta_p^2 = 0.413$ for a linear contrast].

Additional analyses

We also tested for possible changes in motor and judgment behavior in the course of the whole experiment in response to one of the reviewers' comments. An absolute motor error was computed as a difference (unsigned) between the reproduced cursor distance and the size of the square. This error was largest for the practice block, and it decreased until the second regular block and did not change substantially thereafter [see Fig. S2 (A) in the supplementary materials for means]. An ANOVA including block as a factor, mean absolute error as a dependent measure, and the data of all blocks (including the practice and learning blocks) revealed a significant main effect of block for the finger judgments trials, $F(5, 75) = 9.31$, $p < 0.001$, $\eta_p^2 = 0.383$ as well as for the square judgments trials, $F(5, 100)=23.13$, $p<0.001$, $\eta_p^2=0.536$. Both effects were not significant when the first two blocks (i.e., practice and the first learning block) were excluded from the analyses, $F(3, 45)=2.48$, $p=0.073$, $\eta_p^2=0.142$, and $F(3, 60)=0.42$, $p=0.737$, $\eta_p^2=0.021$.

In a similar vein, the impact of movement transformation on the judgments of finger distance and square size did not change during the four blocks included in the main analyses [see Fig. S2 (B) and (C) in the supplementary materials]. There were, however, some obvious changes when the practice and the first learning block were considered. The effect in the finger judgments was not observed in the practice trials and emerged in the first learning block. The effect in the square judgments, in contrast, seemed to be present already during the practice block and to be even larger as compared to the following blocks of trials. Due to missing values, the initial practice block did not enter the following analyses. An ANOVA with movement transformation, square size, and block as factors performed on the finger judgments revealed a significant interaction between block and movement transformation, $F(12, 180)=2.03$, $p=0.024$, $\eta_p^2=0.119$. This interaction was no longer significant when the first regular block was excluded from analyses, $F(9, 135)=1.02$, $p=0.428$, $\eta_p^2=0.064$. For the judgments of the square, there were no significant movement transformation x block interaction regardless of whether or not the first regular block was included [$F(12, 240)=0.90$, $p=0.550$, $\eta_p^2=0.043$ and $F(9, 180)=0.83$, $p=0.586$, $\eta_p^2=0.040$].

The results of these additional analyses thus suggest that there were some learning-dependent changes in judgment behavior and motor performance during the practice and first regular block. Note that following the instructions, the participants knew about the approximate finger distance required during motor execution and thus could anticipate the consequences of their movements. Accordingly, the assumed perceptual attraction between visual- and body-related signals could take place from the first trial on. However, in an early phase of the experiment, the motor programs have to be fine adjusted and the judgment tasks have to be learned. This could have had an impact on the results and can possibly explain some observed differences in the development of changes related to movement transformation between finger and square judgments in the initial practice trials. In particular, the finger judgment task was much more demanding (esp. because the participants were prompted to explicitly think about the forthcoming movement) than the square judgment task (in which the size of a just seen object was estimated). As a consequence, the square could have received less attention during the finger judgments and thus could impact the judgment behavior to a lesser degree than later in the experiment, where the task was handled more automatically. This could explain why the effect of movement transformation needs some practice to emerge for the finger judgments, but is present very early for the square judgments. The rather sticking increase in the effect magnitude for the practice block in the square judgments could be associated with the presence of the experimenter in the lab during this block. The results of this practice block and related conclusions should be considered with caution also to a low number of trials as compared to the regular blocks.

To sum up, the additional analyses revealed some learning-dependent changes in motor and judgment behavior during an early phase of the experiment which are not at odds with the postulated hypotheses and do not limit related conclusions.

Discussion

The main results of Experiment 1 were straightforward. An increase in planned finger distance caused a systematic increase in judgments of target object. Simultaneously, the final finger distance was systematically misperceived during motor preparation depending on its planned magnitude. In particular, larger finger distances were overestimated, whereas smaller finger distances were underestimated. This pattern of results is in line with the proposed hypothesis, suggesting that planning an action triggers sensory integration of multimodal signals. However, the task proved to be rather complex and the data of several participants had to be excluded. This could cast the observed phenomena into doubt.

We also observed that the larger square was underestimated as compared to the smaller square. This effect could originate from general judgments tendencies (e.g., related to the effect of central tendency). It was not affected by the critical manipulation of movement transformation and thus does not influence the drawn conclusions.

Experiment 2

The goal of Experiment 2 was to replicate the results of Experiment 1. We reasoned that one difficulty of the task in Experiment 1 arose from the fact that the type of perceptual judgment was varied within the participants. We thus decided to use this experimental variation as a between-participants factor in Experiment 2. We also doubled the number of trials for each movement transformation and target condition to increase statistical power. The rest of the procedure as well as the hypotheses were the same as in Experiment 1.

Methods

Participants

Twenty-four participants participated in Experiment 2. None of them participated in Experiment 1. All were right-handed and naive to the purpose of the experiment. The sample included 19 females and 5 males (M_{age} = 25, SD = 4). The participants gave their written informed consent for the procedures and received monetary compensation for their participation. The sample size was determined a priori.

Apparatus

The apparatus was the same as in Experiment 1. In Experiment 2, we bound the index and the middle fingers of the right hand together to prevent possible exploratory movements of the middle finger during the judgments of finger distance as well as to make the task more comfortable to the participants.

Stimuli and procedure

Stimuli and procedure were the same as in Experiment 1 except that only one judgment type was required of each participant.

Design

One-half of the participants were asked to estimate the size of the square, the other half estimated finger distances (random assignment). For each judgment group, there were two experimental factors [movement transformation (4 levels) and square size (2 levels)], which were the same as in Experiment 1. The main experiment included 5 blocks of 64 trials each (8 repetitions of each condition in each block). The order of conditions was random. Before the main experiment started, each group of the participants performed 24 practice trials which were not included in the analyses (12 small squares, 12 large squares, and 6 repetitions of each movement transformation condition). In addition, the first regular block was considered as learning block and was not included in the main analyses as in the previous experiment.

Data preprocessing

Data preprocessing was performed in the same way as in the previous experiment. In square judgment group, three participants did not adapt their finger distance to the four movement transformation conditions (see upper part of Fig. S3 in the supplementary materials). In the finger group, one participant expressed the same behavior (see upper part of Fig. S4 in the supplementary materials) and the judged finger distance in three other participants did not vary with movement transformation (see lower part of Fig. S4 in the supplementary materials). The data of these participants were not included in the analyses.

Results

Square judgments

An ANOVA including movement transformation and square size as within-subjects factors revealed significant main effects of movement transformation, $F(3, 24) = 5.87$, $p = 0.004$, $\eta_p^2 = 0.423$, and square size, $F(1, 8) = 14.44$, $p = 0.005$, $\eta_p^2 = 0.644$. The interaction was not significant, $F(3, 24) = 0.60$, $p = 0.620$, $\eta_p^2 = 0.070$. As in Experiment 1, the lager square was underestimated as compared to the small square. Importantly, an increase in the finger distance to cursor distance ratio caused an increase in judged size of the square, $F(1, 8) = 6.70$, $p = 0.032$, $\eta_p^2 = 0.456$ for a linear contrast (see left part of Fig. 6 for means).

Finger judgments

As in Experiment 1, significant main effects of movement transformation, $F(3, 21) = 10.53$, $p < 0.001$, $\eta_p^2 = 0.601$, and square size, $F(1, 7) = 6.45$, $p = 0.039$, $\eta_p^2 = 0.480$, were evident in an ANOVA including movement transformation and square size as factors. The interaction was not significant, $F(3, 21) = 2.39$, $p = 0.098$, $\eta_p^2 = 0.255$. The judged finger distance increased with an increase in square size. More importantly, an increase in the finger distance to cursor distance ratio was associated with an increase in constant errors, $F(1, 7) = 10.46$, $p = 0.015$, $\eta_p^2 = 0.599$ for a linear contrast (see right part of Fig. 6 for means).

Additional analyses

The absolute motor error strongly decreased until the second regular block and remained approximately constant in the further course of the experiment [see Fig. S5 (A) in the supplementary materials for means]. An ANOVA including block as a within-subject factor and type of judgment (finger, square) as a between-subject factor revealed a significant effect of block when all six blocks entered the analyses, $F(5, 75) = 11.95$, $p < 0.001$, $\eta_p^2 = 0.443$. This effect was no longer observed when the first two blocks were excluded, $F(3, 45) = 0.71$, $p = 0.551$, $\eta_p^2 = 0.045$.

Similar to Experiment 1, the effect of movement transformation in the finger judgments was rather small in the initial blocks of trials and seemed then to increase [see Fig. S5 (C) in the supplementary materials]. In contrast to

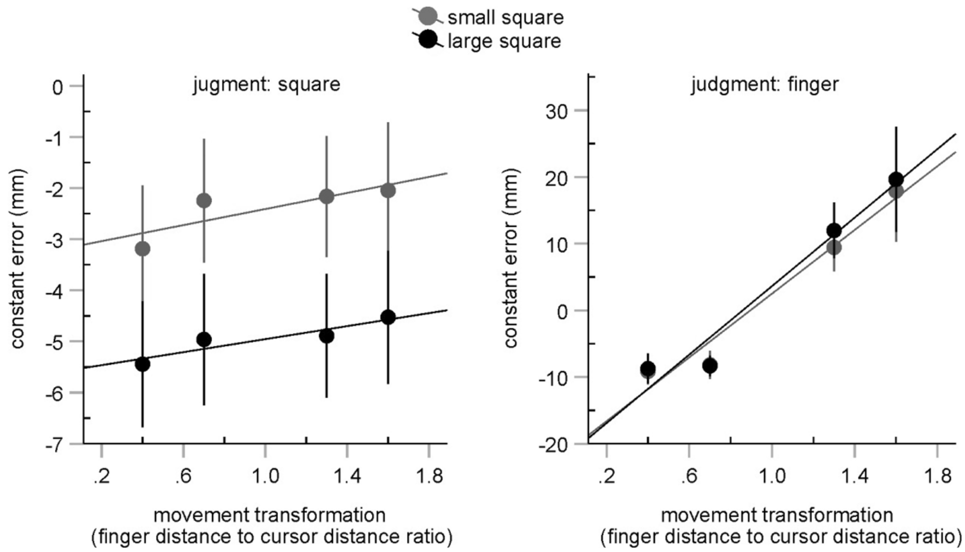

Fig. 6 Main results of Experiment 2. Error bars are standard errors (between-participants). Positive constant error values reflect overestimation, and negative values indicate underestimation

Experiment 1, this effect seemed to be present already during the practice block. This is probably due to a double number of trials in this block in Experiment 2. The effect in the square judgments seems to be present from the initial block on in which it seems to be stronger pronounced than in the following blocks [see Fig. S5 (B) in the supplementary materials]. An ANOVA including the finger judgments revealed a marginally significant interaction between the factors movement transformation and block when all blocks except for practice were considered, $F(12, 84) = 1.73$, $p = 0.076$, $\eta_p^2 = 0.198$. This effect was significant when the learning block was excluded from the analysis, $F(9, 63) = 2.14$, $p = 0.039$, $\eta_p^2 = 0.234$. This is another small deviation from the results of Experiment 1 and relates to the fact that the effect is somewhat smaller in the second regular block than in the following blocks. As in Experiment 1, there were no significant interactions between the factors movement transformation and block for the square judgments irrespective of whether the learning block was included [$F(12, 96) = 0.60$, $p = 0.834$, $\eta_p^2 = 0.070$ and $F(9, 72) = 0.50$, $p = 0.872$, $\eta_p^2 = 0.058$]. By and large thus, the results of the additional analyses were the same as in Experiment 1.

Discussion

Experiment 2 revealed the same results as Experiment 1. That is, the judgments of the target object increased with an increase in planned finger distance. In addition, larger finger distances were judged as larger and smaller distances as smaller during their planning. Thus, both effects appear to be robust phenomena.

Experiment 3

With Experiment 3, we aimed to approve the logic of Experiments 1 and 2 regarding the finger judgments. In the previous experiments, we asked the participants to judge their finger distance that they have to adopt later on after they were informed about its magnitude. We reasoned that during the judgment procedure, the participants would visually imagine the outcome of their action after this action was already planned and multisensory integration had taken place (see "Experiment 1"). However, we do not know for sure whether this was in fact the case. For example, participants could also directly use the original motor command during the judgement to derive the final finger distance. In this case, the results would be inconsistent with the multisensory perspective.

We thus decided to use a more direct measure in Experiment 3 which would enable to evaluate the results of Experiments 1 and 2 and to draw better justified conclusions. We did no longer prompt the participants to think about the forthcoming movement during the judgment procedure and could so rule out the impact of this additional transformation process. Instead, the participants were asked to adjust their fingers to a pair of visual markers which were placed at a pre-specified distance after the movement cue and the target object were presented and before the planned grabbing action was executed. The rest of the procedure was the same as in the finger judgment group of Experiment 2. We thus directly measured the perception of a finger distance following a very clear rationale: When the current (i.e., bodily sensed) finger distance is perceived as smaller, the participants will move the fingers further apart to equalize the perceived distance with the given visual stimulus. And, vice versa, when the current finger distance is felt as larger the

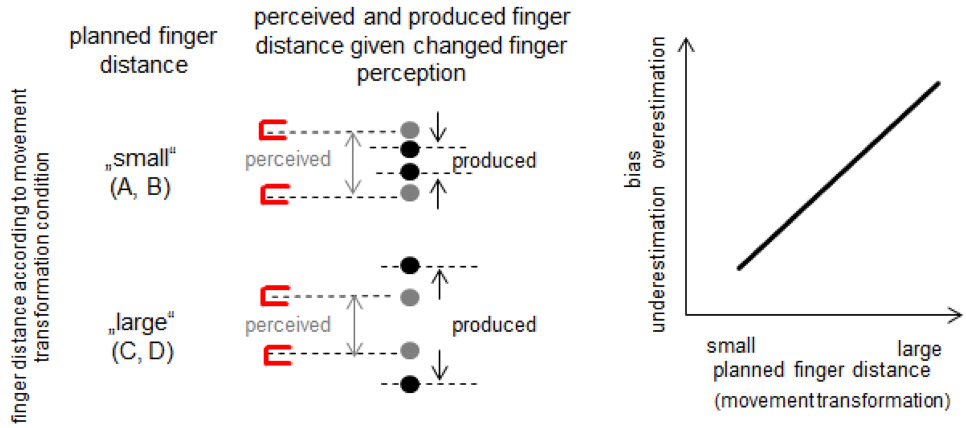

Fig. 7 Rationale and prediction for finger judgments in Experiment 3. Participants adjusted their fingers to a certain distance between two visual markers after they saw a movement cue and the critical target object as in Experiments 1 and 2. The rationale and prediction were straightforward. The felt finger distance will be adjusted to the distance between the visual markers. As a result, perceptually enlarged/compressed finger distances (i.e., "small"/"large" planned distances) should be under-/overestimated by this method of manual distance reproduction

participants will move the fingers closer together to compensate for this change (see Fig. 7). The main hypothesis was the same as in Experiments 1 and 2 (see "Experiment 1"). That is, planned finger distance and visual object information will be integrated. As a result of a spatial discrepancy between both, changes in body perception will emerge.

In Experiments 1 and 2, we focused on the perception of planned finger distance. However, the previous research suggests that any finger distances should be misperceived in the predicted direction. For example, after using a tool held in the hand to manipulate a distant object, the arm is perceived as elongated and this affects the kinematics of subsequent movements without the tool (Cardinali et al. 2009; see also Sposito et al. 2012). Thus, introducing a spatial discrepancy between effector and an external object being manipulated induces perceptual changes not only in a certain part of the effector or in its certain movement, but also in the morphology of the whole effector and these changes are expressed in effector's movements. Applied to the current paradigm of virtual grasping, this finding indicates that any finger distances should be perceived as larger after small as compared to large finger distances are planned. Note that the perceptual bias is defined by subtracting the visual distance between the markers from the produced finger distance in Experiment 3. This leads to the same prediction as in Experiments 1 and 3. That is, an increase in planned finger distance should increase the judged distance (see above and Fig. 7). Finding this effect would substantiate the logic used in the previous experiments and provide an additional clue for the sensory integration during planning of goal-directed actions.

More formally, in contrast to Experiments 1 and 2, in which the distance between visual markers was adjusted to the visual finger distance (S_{visual}), the judgment procedure of Experiment 3 requires an adjustment of a body-related representation of finger distance (S_{body}) to the distance between visual markers. As in the previous experiments, the movement transformation is expected to affect the mapping between S_{body} and S_{visual}, so that $S_{body} > S_{visual}$ for smaller finger distances and $S_{body} < S_{visual}$ for larger finger distances. By definition, a perceptual bias is now given by O_{body} (real finger distance)—the distance between visual markers (i.e., S_{body}), where O_{body} corresponds to S_{visual}. Accordingly, this measure informs about the difference between S_{body} and S_{visual} by S_{visual}–S_{body} as in the previous experiments. Thus, smaller bias values are again expected for the smaller and larger values for the larger finger distance conditions.

Methods

Participants

Twelve participants participated in Experiment 3. None of them participated in Experiments 1 and 2. All were right-handed and naive to the purpose of the experiment. The sample included eight females and four males (M_{age} = 24, SD = 5). The participants gave their written informed consent for the procedures and received monetary compensation or course credit for their participation. The sample size was determined a priori.

Apparatus

The apparatus was the same as in Experiment 2.

Stimuli and procedure

Stimuli and Procedure were the same as in the finger judgment group of Experiment 2 except for the following change. In Experiment 3, we asked the participants to transform a visually sensed distance into the finger distance by means of finger movements. In particular, after the square disappeared, a pair of red U-shaped objects appeared (same as in the previous experiments). The distance between these objects always amounted 4 cm (between the inner parts). The task was to place the fingers at the same distance to each other. This judgment was confirmed by pressing the middle mouse button with the left hand. Then, a pair of dark-gray arrows was presented (cf. "Experiment 1"). This was a signal to move the fingers to the staring position (i.e., to each other).

Design

The design was the same as in each judgment group of Experiment 2.

Data preprocessing

Data preprocessing was performed in the same way as in the previous experiments. In Experiment 3, one participant did not substantially adapt the finger distance during the grabbing according to the factor movement transformation (see upper part of Fig. S6 in the supplementary materials). The data of this participant were not included in the analyses. The finger judgments of another participant strongly scaled with the finger distance to cursor distance ratio (see lower part of Fig. S6 in the supplementary materials). Note that this behavior is well in line with what we have predicted. However, such a behavior could also indicate that this participant systematically tried to grab the square during the judgment. We thus pursued a conservative approach and excluded the data also of this participant from the analyses.

The constant error was computed as a difference between the estimated finger distance and the distance between the visual markers (i.e., finger distance minus visual distance). Positive values reflect thus overestimation of visual distance (and underestimation of felt finger distance), and negative values indicate underestimation of visual distance (and overestimation of felt finger distance).

Results

Finger judgments

An ANOVA including movement transformation and square size as within-subjects factors revealed a significant main effect of movement transformation, $F(3, 27) = 3.07$, $p = 0.045$, $\eta_p^2 = 0.254$. Neither the main effect square size nor the interaction was significant, $F(1, 9) = 2.17$, $p = 0.175$, $\eta_p^2 = 0.194$, and $F(3, 27) = 0.71$, $p = 0.554$, $\eta_p^2 = 0.073$, respectively. The constant error increased approximately linear with an increase in the finger distance to cursor distance ratio as predicted, $F(1, 9) = 4.24$, $p = 0.070$, $\eta_p^2 = 0.320$ (see Fig. 8 for means).

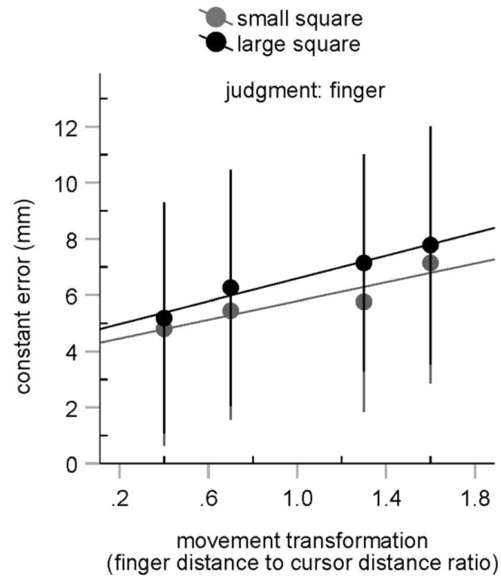

Fig. 8 Main results of Experiment 3. Error bars are standard errors (between-participants). Positive constant error values reflect overestimation, and negative values indicate underestimation

Additional analyses

As in Experiments 1 and 2, the absolute motor error strongly decreased from the practice to the second regular block and did not change substantially thereafter [see Fig. S7 (A) in the supplementary materials for means]. An ANOVA revealed a significant main effect of block when all six blocks were included in the analyses, $F(5, 45) = 8.90$, $p < 0.001$, $\eta_p^2 = 0.497$. This effect disappeared when the first two blocks were excluded, $F(3, 27) = 1.41$, $p = 0.261$, $\eta_p^2 = 0.136$. The impact of movement transformation on finger judgements did not differ across the blocks regardless of whether the first learning block was included or not [$F(12, 108) = 0.62$, $p = 0.825$, $\eta_p^2 = 0.064$ and $F(9, 81) = 0.73$, $p = 0.677$, $\eta_p^2 = 0.075$, see Fig. S7 (B) in the supplementary materials for means]. The later result slightly deviates from that observed in Experiments 1 and 2, where the effect of movement transformation tended to be smaller in the initial blocks of trials and then to increase. Note, however, that the finger judgment task is much easier in Experiment 3 than in the previous experiments. Thus, it seems not surprising that the course of the effect resembles that of the square judgments which were also rather easy (see also the results section in "Experiment 1").

Discussion

An increase in the planned finger distance was associated with an increase of constant error. This predicted result indicates an attraction of the perceived finger distance towards the current target size and is thus in line with the multisensory hypothesis. In addition, it approves the logic applied in Experiments 1 and 2 regarding the finger judgments in that it conceptually replicates the results of Experiments 1 and 2 using a different and more direct methodical approach avoiding several additional assumptions.

General discussion

The present study examined an impact of action planning on visual and body perception in the context of a virtual grasping task. The magnitude of the finger distance required for grabbing a visual object was experimentally varied. The results revealed systematic distortions in the perception of the object as well as of the finger distance, while an action was prepared, but before it was actually executed. We assume that these distortions are perceptual consequences of integrating predicted body-related and actually present visual information relating to an external object during action planning. This suggests that the sensory integration of multimodal signals is not limited to currently available afferent information, but can also rely on predicted re-afferent input.

The ideomotor research explicitly deals with such action–effect anticipations. According to this approach, actions are represented by their body-related as well as environment-related effects. However, the relation between both is not well understood thus far (e.g., Pfister 2019). The multisensory perspective adopted here suggests to consider both types of action effects as redundant, i.e., as related to the same object or event, even though the signals are spatially separated. Using a cursor-control task, Debats et al. already demonstrated that the mutual attraction between the bodily sensed hand position and the visual position of a cursor moving in a different spatial plane is due to a reliability-based weighting consistent with a statistically optimal multisensory integration (Debats et al. 2017a, b). Accordingly, the perceptual system obviously treats body-related and visual movement effects as a single event also when they have different origins (cf. also Helbig and Ernst 2007; Takahashi et al. 2009; Takahashi and Watt 2014, 2017; for related studies). Thus, what is anticipated during action planning is a multimodal percept of an external object or event including body-related as well as environment-related information according to the multisensory perspective.

This view seems to be at odds with studies demonstrating the predominance of environment-related effects in tool use at first glance (see Sutter et al. 2013, for a review). For example, Müsseler and Sutter (2009) showed that participants are widely unaware of their hand movement when they draw circles on a display placed in front of them by moving the hand on a horizontal plane, while the relation between hand and cursor movement is distorted. In a similar vein, when the spatial relation between cursor and hand movements is varied, the perception of the hand movement is usually strongly biased towards the cursor movement (e.g., Ladwig et al. 2012; Sutter et al. 2008). The inverse bias is either substantially smaller or even not detectable at all (Ladwig et al. 2013; Rand and Heuer 2013, 2016; Kirsch et al. 2016a). Based on these and similar results, it has been claimed that body-related action effects are generally attenuated or ignored when using tools (e.g., Sutter et al. 2013). However, according to the multisensory perspective, these findings are not surprising. Since the visual signals are usually more reliable in such setups, their contribution to the overall percept is larger than the impact of body-related information. As a result, the overall percept is dominated by visual information. In other words, the body-related information merely receives less weight rather than being ignored nor attenuated.

Mutual interactions between perception and action are often discussed in the context of a theory of event coding, suggesting that perception and action share a common cognitive representation (TEC, Hommel et al. 2001; see also Prinz 1997). This approach basically holds that perceptual biases observed in the context of actions arise as a consequence of the feature overlap between stimuli and responses. That is, when two events, such as a cursor movement and a hand movement, share a common feature (such as "left" on a direction dimension), these events can be assumed to interact. This framework is generally consistent with the multisensory perspective we trace (cf., e.g., Ladwig et al. 2013). For example, one can assume that the basic principles of sensory integration apply during building of feature codes. When two signals, such as a visual and a haptic, convey information about the same environmental characteristic (e.g., size of an object), the produced event file of that object will contain a feature of, e.g., 4 cm, which is the results of optimal visual–haptic integration. In contrast, when the signals are considered as non-redundant (e.g., due to their large discrepancy), they will enter different event files representing different objects or events (i.e., they will not be integrated but kept separate).

There is also another possibility to apply the TEC framework to the results of the present study. Planning a large finger distance, e.g., may activate a feature "large" shared by both perception and action. Accordingly, this activation can then prime "larger" perception during the judgment procedure, irrespective of whether objects or fingers are judged. Although we cannot rule out this possibility in the present study, our previous related research casts doubts on this view. In particular, finger judgments consistently decrease with an increase in finger distance when measured after action execution (Kirsch et al. 2017). Moreover, the judgment by finger movement, as implemented in Experiment 3, has been already approved as indicator of perceived distance (Kirsch et al. 2016b).

To sum up, the present results revealed systematic changes in the perception of objects and of own body depending on characteristics of planned actions. These effects, we believe, are consequences of integrating visual afferences and predicted body-related re-afferences during action planning. This suggests that many perceptual distortions observed in the context of goal-directed actions arise as a consequence of optimal integration of discrepant multimodal signals.

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