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Visual Near Space Is Scaled to Parameters of Current Action Plans

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In the present study, we show that energetic costs of planned hand movements affect the perception of distances in reaching space. In three experiments, participants prepared hand movements that varied regarding movement amplitude or necessary movement force in either a blockwise or trial-by-trial manner. Before actual execution of the action, a visually presented distance had to be estimated. The results show that judgments of visual distances vary as a function of planned movement amplitude and movement force, specifically, when these parameters change rapidly from moment to moment. These findings show that previous reports of influences of action on perception from extrapersonal space and more enduring changes of action potential generalize to grasping space and much more subtle changes of movement effort. How actions affect visual perception might be determined by the changing parameters of current action plans.

Keywords: spatial perception, action, perception-action coupling, embodied cognition

"So near but yet so far". This idiom is typically used to describe the romantic yearning of unfortunate lovers. Yet, it may also describe the impact of behavioral capabilities or limits on visual perception of space. In fact, it has been shown several times that the way we perceive the world depends on our purposes and motor abilities. For instance, if people are encumbered by wearing a heavy backpack, hills appear steeper than without such burdens (Bhalla & Proffitt, 1999). Spatial egocentric distances are typically perceived smaller if participants are using a tool extending their reaching ability (e.g., Berti & Frassinetti, 2000; Farnè & Làdavas, 2000; Gamberini, Seraglia, & Priftis, 2008; Longo & Lourenco, 2006; Lourenco & Longo, 2009; Maravita, Husain, Clarke, & Driver, 2001; Maravita, Spence, Kennett, & Driver, 2002; Witt, 2011a; Witt & Proffit, 2008; Witt, Proffitt, & Epstein, 2005). Athletes' performance in sports like golf or American football affects their perception of spatial characteristics of balls or goals such that, for example, goals are perceived larger the better the athletes' performance (Witt & Dorsch, 2009; Witt, Linkenauger, Bakdash, & Proffitt, 2008; Witt & Proffitt, 2005).

Despite criticisms and alternative views on some of these findings (e.g., Durgin et al., 2009; Holmes, Calvert, & Spence, 2004; Shaffer & Flint, 2011; Woods, Philbeck, & Danoff, 2009), the overall picture suggests that visual perception of space cannot be understood as a function of optical and oculomotor information alone. According to action-specific approaches this "angular information inherent in optic flow and ocular-motor adjustments is rescaled and transformed into units related to intended actions" (Witt, Proffitt, & Epstein, 2010; cf. also e.g., Witt, 2011a; Witt & Proffitt, 2008). Such rescaling might be beneficial to increase the fit of actual capabilities and behavioral choices (e.g., to prevent overcharging) or to prompt strategic changes (e.g., further reducing the distance to a to-be-hit object when it looks too small, cf. Witt, 2011b).

Although this general idea has been supported by substantial evidence, the specific nature of the "action scale" that determines the interpretation of visual information and the scaling process itself are not well understood. For example, in perception of hills and distances in extrapersonal space, a scale of energetic costs of walking (i.e., effort) was suggested (cf. e.g., Witt et al., 2010). In studies investigating tool-use in contrast, the scale of "reaching ability" is typically assumed (e.g., Witt, 2011a). Related scales are "action potential" (e.g., Witt et al., 2008) or "joint size" (Linkenauger, Witt, & Proffitt, 2011), and "eye-height" (Twedt, Crawford, & Proffitt, 2012). What is common to all these concepts, however, is that certain aspects of the perceiver's body affect perception to the extent that this body is engaged in real, anticipated, or simulated interaction with the environment (cf. also Proffitt, 2008). In other words, scaling of visual features occurs with respect to those features that are part of a *current action plan*.

This hypothesis predicts that the impact of the body on perception should crucially depend on the type of action that the body is going to be involved in. Testing this prediction requires studies in which observers' action plans are systematically manipulated, and the impact of this manipulation on perception is assessed. There are a few observations of this kind. Tools decrease perceived distances, but they do so only when actors plan to use these tools, not when they just hold them (Witt et al., 2005; Witt & Proffitt, 2008). Likewise, throwing a heavy ball increases perceived distances (compared with throwing a lighter ball), but only when the perceiver intends to throw the ball again, not when he or she plans to walk (Witt, Proffitt, & Epstein, 2004). Planning a hand movement toward an object may enhance processing of object's orientation, but only if the actor is intending to grasp this object, not if

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she or he is intending to point to it (Bekkering & Neggers, 2002; Gutteling, Kenemans, & Neggers, 2011). So there is preliminary evidence that the type of planned actions determines whether these actions affect perception or not.

What we want to show in the present study is that influences of action planning on perception are much more fine-tuned, gradual, and short-termed than just the presence or absence of such influences, as a consequence of a rather crude match between the type of action and the type of perceptual task. Specifically, we argue that, even with the same type of action (pointing in our case), the specific parameters incorporated in the current action plan (such as movement amplitude or force) bias space perception. We will refer to this idea as the *motor-planning hypothesis* of action-perception effects. We will explore this idea by informing participants in advance about the parameters of a later to-be-performed action. While being prepared to carry out that action, a spatial distance judgment is obtained. The crucial question is to which extent the specific parameters of that action affect spatial perception.

Studying action effects on perception in that way has two methodical advantages. First, explicitly manipulating to-be-carried-out actions may help to resolve ambiguities of correlational data from previous studies. It has been shown, for example, that day-by-day variability of sport actions correlates with perception of target goals of that sport, such that softball players having a good day see balls as larger (Witt & Proffitt, 2005) or golfers see holes as bigger than on bad days (Witt et al., 2008). Witt and Dorsch (2009) reported that postkicking perceptual judgments were correlated with performance indexes in American football, whereas prekicking judgments were not. Moreover, performance errors were shown to have an impact on specific aspects of perception. These observations certainly suggest an impact of motor performance on perception. Still the correlative nature of the design lacks the criterion of experimental manipulation of the independent variable. Experimentally manipulating action plans and demonstrating an influence of this manipulation on perception would support the inference of a causal impact of motor performance on perception that cannot be obtained from correlational data alone.

Second, it is hard to say which actions are planned, imagined, or simulated if instruction does not clearly tell what to do, and the experimental protocol does not test afterward that this preparation actually took place. By measuring the actions carried out after the perceptual judgment, we have far better control of whether participants actually prepared the action they were told to prepare.

We used a methodically improved version of the setup of a previous study (Kirsch, Herbort, Butz, & Kunde, 2012, cf. Figure 1). At the beginning of each trial, participants saw a cue that informed them which movement had to be executed after a subsequent distance judgment. After this cue disappeared, two visual stimuli were presented on the horizontal plane, whose distance had to be judged. Following this estimate, participants executed a hand movement. The amplitude or force of the movement (or both) varied according to the instructional cue presented before distance judgment. The main question was whether planning a movement of large amplitude and of large force (and hence increased movement effort) causes an increase in perceived distance as compared with planning a movement of small amplitude and of small force (and hence lower effort). This setup allowed us to address two issues.

First, with this task, the perceptual distance judgment as well as the pointing task take place in near space or grasping space. This should help to remove uncertainty about the existence of influences of action planning on perception in near space. These uncertainties exist at both the theoretical and empirical levels. On the theoretical side, it has been suggested that action planning and conscious visual perception work largely independently of each other in grasping or pointing (Milner & Goodale, 1995). For example, visual perception apparently does not affect grasping or pointing (Haffenden & Goodale, 1998; but see Franz, Gegenfurtner, Bülthoff, & Fahle, 2000). If such encapsulated processing of action planning on visual perception in object-oriented movements really exists, it might well be that action planning cannot affect visual perception in gasping space. On the empirical side, influences of planning near-space actions on visual perception have barely been studied so far. Most previous studies that examined perception of space within reach focused on a possible interaction between near and far space following tool use, which is only indirectly interpreted as a temporary extension of near space (e.g., Berti & Frassinetti, 2000; Làdavas, & Serino, 2008). Demonstrating clear influences of actions in near space on perception in near space will remove that empirical ambiguity. Some related evidence has been recently reported by Gutteling and colleagues (2011; cf. also Bekkering & Neggers, 2002). In this study, participants performed grasping and pointing movements while simultaneously performing an orientation-discrimination task. Increased perceptual sensitivity was observed for planning of grasping movements for which objects' orientation was relevant, as compared with planning of pointing movements (see also above).

Second, we employed an action that was essentially the same, with only certain aspects (amplitude and force) of that action to be manipulated. Thus, from the perspective of motor-planning research, it can be said the basic action schema remained the same but certain parameters were changed (Rosenbaum, 1980). By doing so, we can clarify to which extent transient aspects of performance impact perception. There is some indirect evidence that short-term variations of motor abilities might be more important than enduring performance levels. In golf players, the daily performance did correlate with perceived size of golf holes, whereas the more stable handicap did not (Witt et al., 2008). To which extent moment-to-moment changes of action plans impact visual perception is yet unknown. We addressed this issue by combining blockwise and trialwise manipulations of amplitude and force parameters.

Overview of Experiments

We present here three experiments that used the described "perception while action planning" setup. These experiments vary in regard to the way movement parameters are manipulated. In Experiment 1, movement amplitude was manipulated trialwise, and movement force was manipulated blockwise. This blockwise versus trialwise manipulation was switched in Experiment 2. Finally, in Experiment 3, both parameters varied in a trialwise manner.

Experiment 1

In far space, there is evidence that energetic factors of walking or throwing contribute to the awareness of perceived slopes and distances: Hills are judged to be steeper and distances to be further if anticipated metabolic action costs increase, for example, by a heavy backpack (e.g., Proffitt, Stefanucci, Banton, & Epstein, 2003; Witt et al., 2004; see also Proffitt, 2006 and Proffitt, 2008 for reviews). Taking our motor-planning hypothesis as a premise, one can assume that variables possibly used as reference units for perception are derived from planning of locomotion which includes evaluation of movement costs in addition to the specification of other variables. Thus, manipulating one of the variables of a motor plan should cause changes in perception of relevant stimulus dimensions (such as orientation, extent, direction, size, etc.) across a variety of motor acts and perceptual characteristics. If so, then planning of motor acts other than locomotion (e.g., those that include evaluation of movement costs) can also be expected to affect perception.

It is well-known that motion characteristics of simple point-to-point hand movements are the result of cost-effective planning and control strategies (e.g., Flash & Hogan, 1985; Harris & Wolpert, 1998; Uno, Kawato, & Suzuki, 1989). Costs are usually assumed to increase if movement amplitude, movement duration, or joint driving forces increase (cf. e.g., Harris & Wolpert, 1998). Accordingly, we assume that the variation of anticipated movement costs (or effort) in hand movements will affect perception of distances to which movements are related.

The purpose of Experiment 1 was twofold. First, we aimed to conceptually replicate the effect of varying movement amplitude on distance perception found in a previous study (Kirsch et al., 2012). Second, we tested whether a more direct manipulation of anticipated movement costs causes changes in perception if other movement parameters are held constant.

There were two key independent variables. First, in each trial, participants received a cue that informed them whether a movement should have an extent of 150% (long) or of 50% (short) with respect to a target distance. which had to be estimated after the cue disappeared and before the movement had to be executed. Second, we used a force device that allowed us to manipulate external forces (low or high forces) acting opposite to the direction of the hand movement. We expected to find an increase in estimated distance with an increase in extent of a planned movement and with an increase in force applied to the hand, which should cause an increase in effort needed to achieve an intended movement goal.

Method

Participants. Twenty-four participants were recruited. They gave their informed consent for the procedures and received an honorarium or course credit for their participation. One participant was excluded from analyses due to reduced vision not corrected by contact lenses or glasses. Another participant violated the movement instructions. His data were also discarded. The final sample included 16 women and six men. All of them reported being right handed. The mean age was 24 years, ranging from 20 to 29 years of age.

Apparatus. The main apparatus included a digitizing tablet (Wacom Intuos 2 A4, Vancouver, WA), a digitizing stylus, a monitor, and a semisilvered mirror (see also Figure 1 in Kirsch et al., 2012; also cf. Ghahramani, Wolpert, Jordan, 1996). The monitor and the mirror were positioned above the tablet, which was placed on a table. The mirror was placed approximately midway between the tablet and the monitor (i.e., about 24 cm above the tablet and below the monitor). When the light was dimmed, the mirror prevented direct view of the arm, but enabled projection of virtual images of the monitor in the plane of the tablet. One picture element (PEL) of the monitor measured about 0.38 mm on the screen. When feedback of a movement executed on the tablet was presented, the relation between the actual position of the stylus and stimulus position indicating the position of the stylus were adjusted so that feedback approximately corresponded to the real stylus position (i.e., we did not manipulate visual feedback).

A secondary apparatus we used consisted of an electric motor that could produce force of varying magnitude. The motor was connected with the digitizing stylus by means of a cord (see Figure 1). The stylus was clamped in a holder so that it could stand alone, upright. When the motor was turned on, it pulled the stylus along the tablet in the direction of the participant's body midline on the level of the waist. That is, when the participant had to move the stylus away from the body, he had to overcome the force produced by the electric motor.

Procedure and design. Participants sat in front of the apparatus so that the position of the body midline corresponded with the middle of the monitor and of the tablet. Moreover, in order to keep the position of the head constant, we asked each participant to lean his or her forehead on an upper part of the main apparatus during the experiment. Participants were asked to perform stylus movements with the right hand, whereas distance judgments had to be performed with the left hand.

The main trial procedure is shown in Figure 2. Each trial started with a movement of the stylus to the start position, which was located in the middle lower part of the tablet (i.e., next to the body at the level of the body midline). After reaching the start position, which had to be approved by pressing a stylus button, a symbolic cue was displayed. This informed the participant to overshoot or to undershoot the target circle by half of the target distance (Figure 2, left). A gray circle (~55 mm) and a gray square (~ 55 × 55 mm) served as symbolic cues, which were framed by a white rectangle 195 × 144 mm in size. The residual display surface was gray. The assignment of the cues to the movement instruction was counterbalanced across participants. The cue disappeared after the participant pressed the space bar.

Following this key press, the start circle appeared together with a target circle in the middle of the otherwise black screen (Figure 2, middle). The circles were gray and had a diameter of approximately 3.5 mm. The position of the start circle corresponded to the starting position of the stylus and was always constant during the experiment. The position of the target circle, in contrast, varied trial by trial.

After the participant pressed a right or a left arrow key on the keyboard, which was placed sidewise of the main apparatus, two additional circles appeared to the left and right next to the midway between the target and start circle (i.e., they arose from a central position located between the start and target circles). These additional circles were the same color and size as the start and target circles. The task was to adjust the horizontal distance between the left and right circles by pressing left and right arrow keys on the keyboard so that it was equal to the vertical distance between start and target circle. There was no time limit for the estimate. Discrete or continuous pressing of one of the arrow keys caused an increase in the distance between the horizontal circles, whereas the other

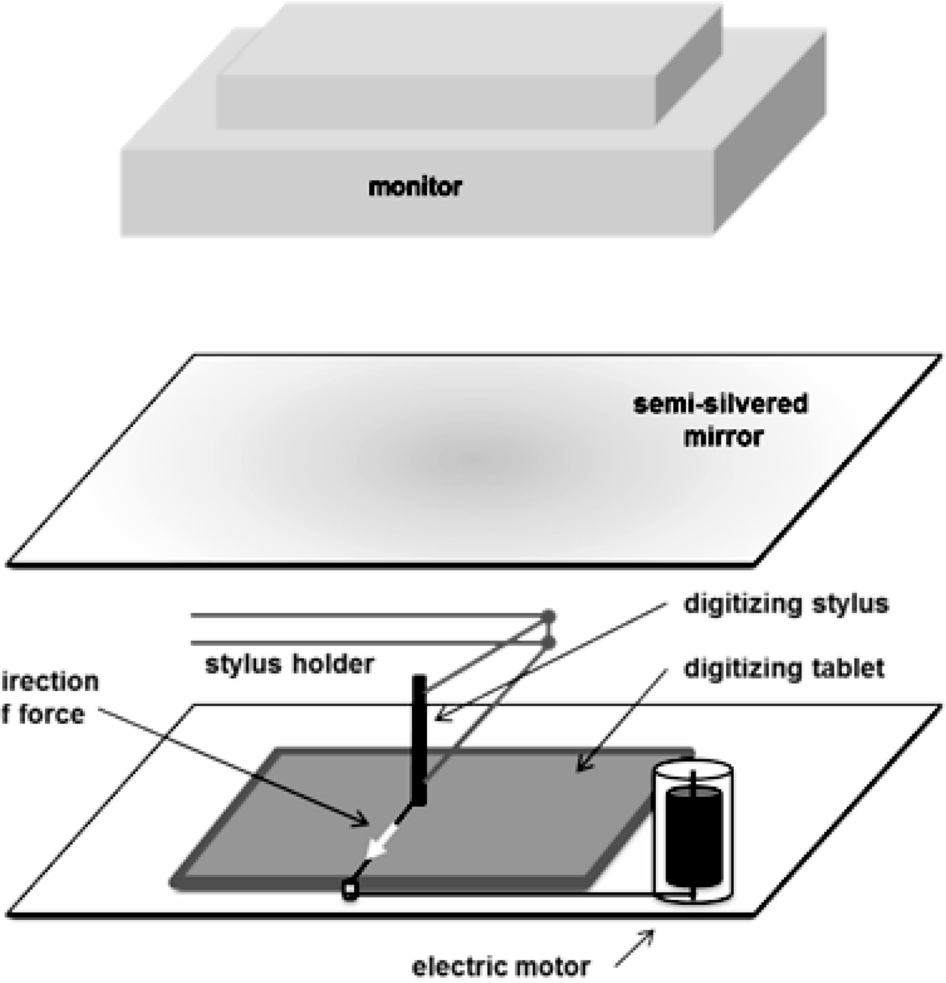

Figure 1. Schematic illustration of the used apparatus.

key was to be used to decrease the distance. Participants were allowed to make discrete as well as continuous adjustments until they were satisfied. During the adjustment procedure, the right and left circles were always equidistant with respect to the start and target circles. The enter key of the keyboard was used to complete the adjustment procedure.

In response to this key press, all stimuli disappeared and the current stylus position was displayed as a green circle (3.5 mm). This served as a go signal to initiate a stylus movement according to the movement instruction (cf. Figure 2, right). After the participant finished the movement he or she had to press a stylus button. Following this button press, a red circle (∼2 mm) was displayed at the starting position together with a short text asking the participant to move the stylus back to the start position.

There were three independent variables. First, *the target distance*, that is the distance between the start and target positions, was varied between 179 PEL and 287 PEL in steps of 36 PEL (i.e., there were four target distances). Second, the *movement instruction* could be to overshoot (150%) or to undershoot (50%) the target by half of the target distance. Third, *external force* produced by the force device was either ∼100 or ∼900 g. These forces can be assumed to be clearly discriminable as just noticeable differences for forces, and weights are typically between 2 and 12% (e.g., Jones, 1986).

The force device was programmed so that force was applied for the duration of 5 s (due to technical reasons) after the distance estimate was confirmed by a button press. In response to this go signal, participants were required to perform target movements as rapidly and as accurately as possible. In contrast, in case of distance judgments, the instruction stressed accuracy only.

The experiment contained two blocks of 32 trials. In each block each combination of movement instructions (two) and stimulus distances (four) was presented four times in a randomized order. The manipulation of external force, in contrast, was implemented blockwise. That is, before each block, participants were informed about which of two force levels would be used. The order of force levels was counterbalanced across participants. Before the start of the regular blocks, participants were familiarized with the apparatus and the task by performing eight practice trials (four with each force level).

Data recording and analysis. The recorded amplitude of the stylus movement was converted into percentage values according to each target distance to measure the performance with respect to the movement instruction (*relative movement amplitude*). In order

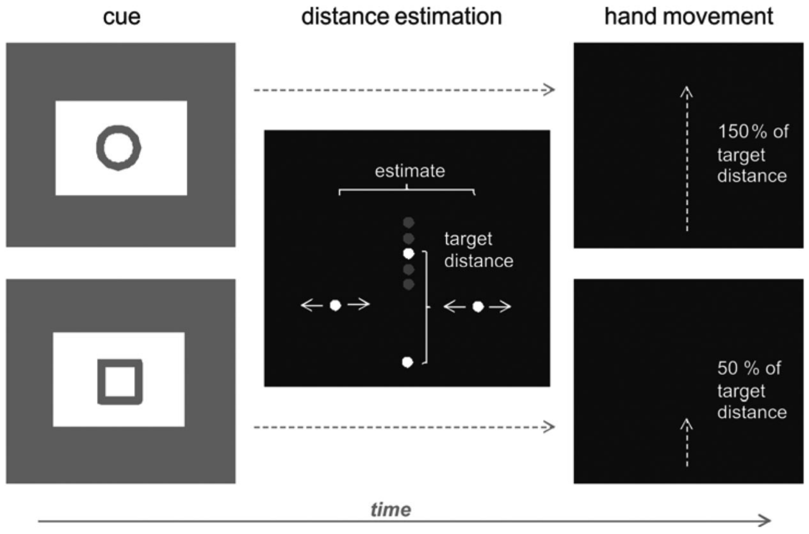

Figure 2. Schematic illustration of the trial procedure. Circles shown in gray are potential target positions, which were not visible in this example. During the hand movement, only the virtual position of the stylus was presented in the form of a green circle (not shown). The movement cue requires participants to prepare a movement that is 50% longer or shorter than a movement to the target.

to measure the accuracy of perceptual judgments, the difference between the distances between the horizontal and the vertical stimuli was extracted after the adjustment of the horizontal stimulus distance (*constant perceptual error*). By definition, positive perceptual error reflects overestimation of the vertical distance, whereas negative perceptual error indicates underestimation of the vertical distance. Trials, in which estimated distances and movement amplitudes were smaller than 100 PEL and 50 PEL, respectively, were considered as outliers and were excluded from analyses. For the remaining trials, the medians movement amplitude and perceptual error were computed for each participant and each experimental condition.

Results and Discussion

Relative movement amplitude. We performed an analysis of variance (ANOVA) including target distance (four levels), movement instruction (two levels) and external force (two levels) as within-subjects factors, and relative movement amplitude as the dependent variable to ensure that participants followed the movement instruction. This analysis yielded significant main effects of movement instruction, $F(1, 21) = 740.0$, $p < .001$, target distance, $F(3, 63) = 6.2$, $p = .001$; and significant interactions between instruction and target distance, $F(3, 63) = 8.6$, $p < .001$, and between all of the factors, $F(3, 63) = 5.0$, $p = .004$. An interaction between external force and target distance was marginally significant, $F(3, 63) = 2.6$, $p = .057$. As shown in Figure 3 (A), participants were able to follow the movement instruction well, performing movements of 56% and of 151% amplitude with respect to the target distance under the movement-instruction conditions of 50% and 150%, respectively.

In addition, both other factors slightly modified the motor performance. When the movement instruction was 50%, the high force level was associated with a trend toward shorter movements than when the force level was low. When the movement instruction was 150%, this trend was observed only for the smaller target distances. We assume that these trends toward underestimation of a given distance under high-load conditions are related to motor execution processes rather than motor planning (cf. Exp. 2 and 3). That is, external force applied during movement may cause an earlier breaking of the movement so that it is finished before the desired end point is achieved. Alternatively or additionally, these trends may also be related to changes in the perception of force following fatigue (cf. e.g., Jones, 1986). That is, subjects may feel that they exert enough force to achieve a desired end point, but due to fatigue they underestimate the required amount of force.

Constant perceptual error. An overview of mean perceptual errors in each experimental condition is given in Table 1.

An ANOVA computed with the constant perceptual errors as the dependent variable, and with target distance, movement instruction, and external force as factors, revealed significant main effects of target distance, $F(3, 63) = 7.8$, $p < .001$, and movement instruction, $F(1, 21) = 6.7$, $p = .017$. The main effect of force as well as a Force × Movement instruction interaction did not reach the significance threshold, with $F(1, 21) = 2.7$, $p = .116$, and $F(1, 21) = 2.1$, $p = .164$, respectively. Also, all other interactions were not significant (all $p > .351$).

Participants tended to overestimate the given target distance on average and this tendency increased with an increase in target distance (see Table 1). This result likely reflects the impact of optical variables associated with a phenomenon called horizontal–vertical illusion, which a tendency to overestimate the length of a vertical line compared with a horizontal line of equal length (e.g., Hamburger & Hansen, 2010). An increase of this bias with target distance probably indicates an increase of this illusion effect.

More important, the tendency to overestimate the vertical distance was more pronounced in the 150% movement instruction condition as compared with the 50% condition (see Figure 3 B). That is, a larger amplitude of the planned movement was associ-

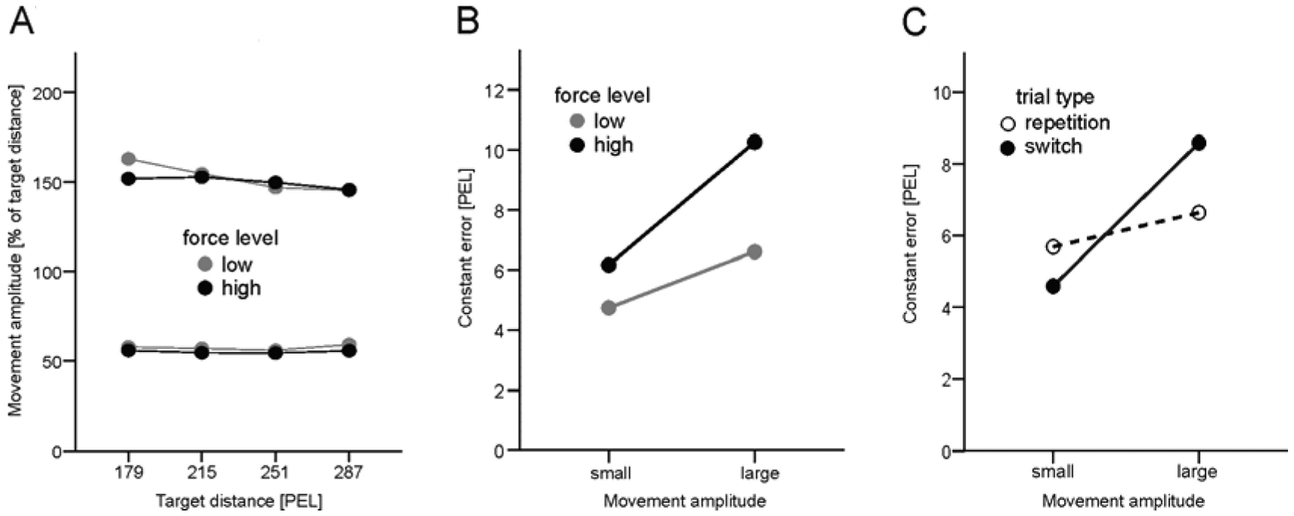

Figure 3. Main results of Experiment 1. Movement amplitude in % of target distance (A). Mean constant error as a function of the movement instruction and the level of force device (B). Mean constant error for movement instruction conditions depending on whether the previous trial ($n - 1$) contained the same or a different instruction.

ated with a stronger tendency to overestimate a given target distance. This predicted finding constitutes a conceptual replication of the results of our previous study (Kirsch et al., 2012) and suggests that parameters of movement planning can affect the subjective representation of a spatial distance.

Surprising, the effect of force manipulation, which captures changes in effort more directly, was less systematic and not significant as compared with the effect of movement extent. Why is this so? It should be noted that movement force was manipulated blockwise and movement extent was manipulated trialwise. It might be that visual perception is affected more strongly by moment-to-moment changes of action plans rather than by those features that remain constant and need not be changed. To explore this possibility we examined the effect of movement extent in more detail. In particular, we tested whether the perceptual judgment in a given trial depends on whether a previous trial had the same movement instruction or not. If an increase in the size of the effect can be observed in trials that were preceded by the opposite movement instruction as compared with repetition trials, then the lack of a significant effort effect may be related to a blockwise manipulation of force.

Figure 3 (C) shows the results of this analysis. We could in fact observe that a significant effect of movement instruction was present in trials preceded by trials with the opposite movement instruction, $t(21) = 3.2$, $p = .005$, but absent in repetition trials, $t(21) = .7$, $p = .505$. Thus, an effect of motor planning on perception was present only when planning parameters changed trial by trial, but not when they remained constant across a few trials.

Experiment 2

The results of Experiment 1 revealed that planning a movement of relatively large amplitude was associated with an increase of the estimated visual distance to which hand motion was related, as compared with the planning movement of relatively small amplitude. In addition, we observed that this effect was evident only when movement instruction changed in successive trials, but not when it was repeated. Yet, no reliable effect of movement force on distance judgments was apparent even though a trend in the expected direction was observed. Based on a trial analysis of perceptual errors we conjecture that the lack of a significant impact of external force variation on perceptual judgments might have been due to a block wise manipulation of force. Accordingly, a possible effect of anticipated movement effort on perception may be demonstrated if movement costs change trial by trial. To test this possibility we performed Experiment 2, in which we inverted the assignment of critical variables, namely movement extent and

Table 1
Mean Perceptual Error Scores (PEL) in Each Experimental Condition of Experiment 1

Target distance (PEL)	179		215		251		287	
Force level	Low	High	Low	High	Low	High	Low	High
Movement amplitude								
Small	1.77 (15.81)	5.00 (14.94)	2.82 (15.80)	3.23 (17.90)	4.23 (19.34)	5.27 (25.27)	10.14 (23.87)	11.14 (24.35)
Large	4.00 (15.28)	6.18 (13.76)	4.95 (19.00)	7.86 (16.91)	5.68 (18.02)	12.55 (20.04)	11.77 (24.58)	14.45 (23.62)

Note. Standard deviations are shown in parantheses.

external force, to the block wise and trial wise presentations. That is, external forces applied to the hand movement could now change within one block of trials, while movement instruction remained constant during each block. We now expected to find a significant effect of force manipulation on perceptual judgments of distances, while the impact of movement extent should now be removed.

Method

Participants. Twenty-four participants were recruited. They gave their written informed consent for the procedures and received course credit for their participation. One participant has to be excluded from the analyses due to data loss (technical reasons). The mean age of the remaining participants was 21 and ranged from 19 to 38 years of age. This final sample included 19 women and four men. Four participants reported that they were left handed.

Apparatus. The main apparatus was the same as in Experiment 1. The force device, in contrast, has been modified so that force produced by the electric motor could be changed within one block of trials. As a result of this modification (and of inattention of the experimenter), the software setting of Experiment 2 produced more force in the high force level condition as compared with Experiment 1 (900 vs. 1200 g).

Procedure and design. The procedure of Experiment 2 was complementary to the procedure of Experiment 1. The instructional cue presented before distance judgment informed the participant not more about the amplitude of the movement which had to be executed after the distance estimate (Experiment 1) but about the force level applied to the movement. And conversely, the manipulation of movement amplitude would now be implemented blockwise. That is, before each block, participants were informed about which movement instructions (50% or 150%) would be used. All other manipulations and details of the procedure, design, recordings, and analyses were the same as in Experiment 1. This also means that left-handed participants were asked to perform stylus movements with their nondominant right hand and perceptual judgments with their dominant left hand.

Results and Discussion

Relative movement amplitude. As in Experiment 1, movement instruction had a strong impact on the amplitude of the executed movements (see Figure 4 A for means). An ANOVA performed on relative movement amplitude including external force, movement instruction, and target distance as factors yielded a significant main effect of movement instruction, $F(1, 22) = 484.6$, $p < .001$. Additionally, a main effect of target distance, a movement Instruction × Target Distance interaction and an external Force × Target interaction were significant with $F(3, 66) = 6.5$, $p = .001$, $F(3, 66) = 9.8$, $p < .001$ and $F(3, 66) = 3.0$, $p = .037$, respectively (all other *p*s > .5).

Similarly to the results of Experiment 1 there was a slight trend toward a decrease of movement amplitude with an increase in target distance for the movement instruction 150% but not for the 50% condition[1] (see Figure 4 A). We speculate that this result might reflect a kind of ceiling effect associated with the awareness of the participants related to the size of the digitizing tablet (e.g., they may have been worried that movements may extend the size of the tablet in case of distant targets).

As in Experiment 1, the manipulation of external force had some impact on movement amplitude, which varied with target distance. As mentioned earlier (see Experiment 1), we assume that these small differences in movement distance between force-level conditions are not primarily related to differences in specification of spatial movement goals. Rather, they may be related to biomechanical constraints and/or afferent processes associated with adding external force. Some discrepancy between Experiment 1 and Experiment 2 would then reflect varying impact of blockwise versus trialwise variation on these factors.

Constant perceptual error. Mean perceptual error values are shown in Table 2.

An analysis of these values by means of an ANOVA revealed significant main effects of movement instruction, $F(1, 22) = 7.4$, $p = .013$, of target distance, $F(3, 66) = 10.0$, $p < .001$ and more important, of external force, $F(1, 22) = 6.6$, $p = .017$[2] (all other *p* values > .233). Analogous to the results of Experiment 1, an increase in target distance was associated with an increase in perceptual error likely reflecting an increase of vertical–horizontal illusion. In contrast to Experiment 1, however, an increase in amplitude of an upcoming movement caused a decrease in estimated distance (see Figure 4 B). Here, no differences were expected based on the results of Experiment 1. We return to this result in the General Discussion section.

The main finding of Experiment 2 was that a change in external force applied to movements that were executed after perceptual judgments modulated perceptual judgments in a predicted manner: An increase in force led to an increase in estimated distance (see Figure 4 B). Thus, the results confirm the assumption that anticipated movement costs are also taken into account in perception of near space. This appears to be true at least if effort can change trial by trial. However, because a slightly larger force level was used in Experiment 2 than in Experiment 1, one cannot rule out that the lack of a significant force effect in Experiment 1 was due to this difference in absolute force level. To explore this possibility, we analyzed the effect found in Experiment 2 in more detail by testing its possible dependency on the order of force levels (see analogous analysis of the effect of movement instruction in Experiment 1). If the difference in absolute force level can alone account for the results (i.e., if trialwise vs. blockwise manipulation does not play a role here), one can assume that the perceptual judgment in a given trial does not depend on whether a previous trial had the same force level or not. In contrast, if an increase in the size of the effect can be observed in trials that are preceded by an opposite force level, as compared with trials preceded by the same force level, then the absolute force level will not exclusively be responsible for the impact on perceptual estimates. The mean values of this analysis are shown in Figure 4 (C).

Analogous to the analysis of the effect of movement instruction in Experiment 1, there was a significant effect of external force in trials preceded by trials with an opposite force level, $t(22) = 4.0$,

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[1] This trend was mainly present for the low level force condition in Experiment 1.

[2] To ensure that this main result was unaffected by the handedness of the participants, we rerun this analysis excluding the left handers. A main effect of external force was still significant with $F(1, 18) = 6.75$, $p = .018$. Thus, the observed impact of force manipulation does not seem to be due to the inclusion of left-handed participants in Experiment 2.

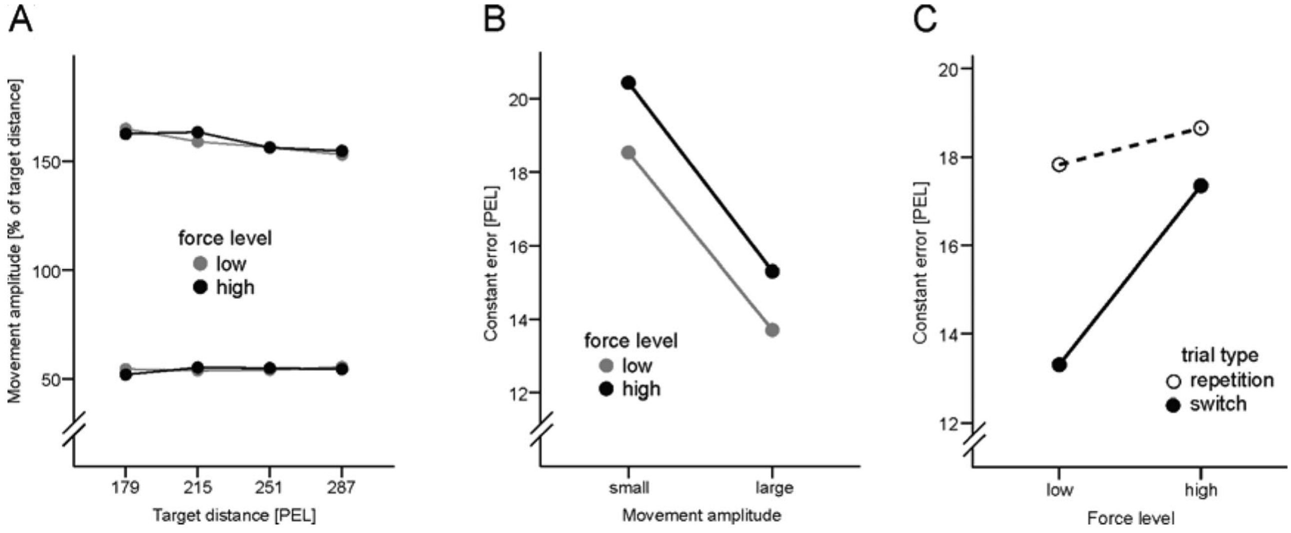

Figure 4. Main results of Experiment 2. Movement amplitude in % of target distance (A). Mean constant error as a function of the movement instruction and the level of force device (B). Mean constant error for movement instruction conditions depending on whether the previous trial contained the same or different instruction.

$p = .001$, in addition to a nonsignificant effect observed in repetition trials, $t(22) = .6$, $p = .553$. Thus, the results suggest that a change of force level rather than the absolute force level substantially contributes to the impact of motor planning on perceptual estimation of distances. It remains possible, however, that the lack of a significant force effect in Experiment 1 was due to a lower force level used in the high force-level condition. Even though both force levels were clearly discriminable for the participants in Experiment 1 as well as in Experiment 2, their measureable impact on perceptual estimates may depend on a certain threshold, that is, on a certain minimal difference between two force levels. Accordingly, it is possible that the force effect was not significant in Experiment 1 because the difference between force levels was lower (~800 g) than in Experiment 2 (~1100 g). Although the trial analysis mentioned above (repetition vs. switch) does not seem to support this possibility, future studies may address more precisely this issue using identical force conditions in block-wise and trial-wise designs.

Experiment 3

The results of Experiment 1 and 2 indicate that the amplitude of a planned movement as well as anticipated movement force affect perception of spatial distances in reaching space. Yet, these experiments suggest that these influences occur in a systematic manner only for the parameter that changes from moment to moment (or trial to trial, to put it more technically). So an experiment suggests itself in which both features are manipulated in such a trialwise manner. This was done in Experiment 3.

The general procedure used in Experiments 1 and 2 was extended by introducing four (instead of two) movement cues. In each trial, each of these four cues was used to simultaneously signal the amplitude of the movement (50 vs. 150%) and the level of external force (100 vs. 1200 g). This manipulation should not only delineate the main effects of both parameters, but their possible interaction.

Consider that changes in muscular effort required to move the stylus under different experimental conditions of the present study may roughly be estimated by considering "work" performed by the muscles. In physics, the mechanical work (W), or energy is the product of force (F) by motion extent (distance; d) through which it acts ($W = F^{*}d$). Due to this multiplicative relation between force and distance, an increase in internal force following an increase in force level produced by the given force device should be associated with greater work for movements of rather large amplitudes than for movements of comparatively small amplitudes. Let's say the external force device requires the hand to increase its internal forces by 2 and 4 units in the low- and high-level conditions, respectively. If the internal forces would be constant over a range of movements[3] and be, for example, 3 units, a movement of 10 units' amplitude would be associated with $(3 + 2) \times 10 = 50$ units of work in the low level condition and with $(3 + 4) \times 10 = 70$ units in the high level condition. For a movement distance of 20 units, mechanical work would reach values of 100 ($[3 + 2] \times 20$) and 140 ($[3 + 4] \times 20$) in the low and high force-level conditions, respectively.

Assuming that anticipated movement effort is related to the anticipated mechanical work of hand motion (cf. e.g., Jones, 1986) one may predict that the impact of force manipulation on distance perception should be smaller when shorter instead of longer movements are planned. Such a pattern would substantiate the assumption of scaling of spatial attributes in near space, according to anticipated effort of a planned movement.

Method

Participants. Twenty-two individuals participated in Experiment 3. They gave their written informed consent for the proce-

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[3] This is usually not the case for simple arm movements. This, however, seems not to be crucial for the present argument.

Table 2
Mean Perceptual Error Scores (PEL) in Each Experimental Condition of Experiment 2

Target distance (PEL)	179		215		251		287	
Force level	Low	High	Low	High	Low	High	Low	High
Movement amplitude								
Small	14.52 (17.45)	14.87 (15.32)	16.43 (18.63)	18.83 (18.35)	18.17 (24.31)	21.35 (23.89)	25.04 (27.27)	26.74 (28.59)
Large	9.65 (16.57)	11.78 (16.10)	9.22 (21.05)	14.74 (21.47)	16.70 (25.18)	14.65 (23.25)	19.26 (32.13)	20.04 (29.12)

Note. Standard deviations are shown in parantheses.

dures and received an honorarium or course credit for their participation. The data of three participants were excluded from analyses. These subjects had difficulties following the movement instructions: One of them consistently ignored the cues requiring changes in amplitude; two others did not consistently make movements. The final sample included 13 women and six men. All of them were right-handed. The mean age was 26 years, ranging from 18 to 52 years of age (*SD* = 7).

Apparatus.

The apparatus was the same as in Experiment 2.

Procedure and design. The general procedure of Experiment 3 was similar to the procedures of Experiments 1 and 2: Visual distances were judged after a movement cue was presented and before movements were executed. The crucial difference was that four movement cues were used instead of two: a white “x” on a gray background, a white “o” on a gray background, a gray “x” on a white background and a gray “o” on a white background. The letters (~45 mm in size) appeared in the middle of the display and informed about the extent of the upcoming movement, which could be either 50 or 150% with respect to the given target distance. The background color informed about the force level to be applied to the movement (100 or 1200 g). The assignment of the cues to the force levels and movement extent was counterbalanced across the participants.

Movement cues were randomly presented within one block of trials. That is, movement extent and force level varied randomly and independently of each other. There were two regular blocks of 32 trials. In each of them, each movement cue was presented twice for each target distance. As in Experiments 1 and 2 there were three independent variables: movement instruction, target distance, and external force.

Before the main procedure, participants performed an additional practice block of 16 trials. In this initial block, each experimental condition was presented once. Before the practice block started, participants received an instruction about the given association between movement characteristics and the cue identity and were asked to learn it. Moreover, participants were informed that this information will be required later. Also, they were encouraged to ask the experimenter if they are not sure how to do the task. (The experimenter was present in the lab during the practice block.) Following the practice block, participants were asked to recall the cue–movement association by means of a four-alternative forced-choice task. In this task, each cue was shown together with four possible Force × Amplitude combinations (50% and high force level, 150% and high force level, 50% and low force level and 150% and low force level). Each participant had to decide which combination was represented by a given cue.

All other manipulations and details of the procedure, design, recordings, and analyses were the same as in Experiments 1 and 2.

Results and Discussion

Relative movement amplitude. An ANOVA performed on relative movement amplitude, including external force, movement instruction, and target distance as factors yielded significant main effects of movement instruction, $F(1, 18) = 651.2$, $p < .001$, and of target distance $F(3, 54) = 14.2$, $p < .001$, and a significant interaction between both, $F(3, 54) = 15.1$, $p < .001$ (all other ps $> .231$). As shown in Figure 5 (A), participants consistently followed the movement instruction, reaching 163% and 59% of target amplitude on average in the movement instruction Conditions 150 and 50, respectively. Moreover, analogously to the results of Experiments 1 and 2, there was a decrease in movement amplitude with an increase in target distance for the movement instruction at 150%, but not for the 50% condition. All other trends relating to the force manipulation found in the previous experiments were not observed, suggesting that those trends were the result of differences in motor execution, which were somewhat differently pronounced in blockwise and trialwise designs, as mentioned earlier.

Constant perceptual error. An overview of mean perceptual errors in each experimental condition is shown in Table 3.

An ANOVA performed with the constant perceptual errors as the dependent variable and with target distance, movement instruction, and external force as independent variables revealed a significant main effect of movement instruction, $F(1, 18) = 12.5$, $p = .002$, and a significant Instruction × External Force interaction, $F(1, 18) = 4.4$, $p = .05$ (all other main effects and interactions were not significant with ps $> .363$). As shown in Figure 5 (B), participants overestimated the given target distance more strongly when they prepared a movement of a large amplitude, as compared with planning for a small one. This result is in line with the results of Experiment 1 in which movement instruction was also varied trial by trial. More important, however: This effect was modified by variation of the external force. An increase in force level was associated with a significant increase in distance estimates when the movement amplitude was relatively large, $F(1, 18) = 7.5$, $p = .014$. In contrast, there were no significant differences between the force levels when the movement amplitude was relatively small, $F(1, 18) = .3$, $p = .604$.

These results highlight two points. First, the effect of movement instruction on perceptual judgments in Experiment 2 was conceiv-

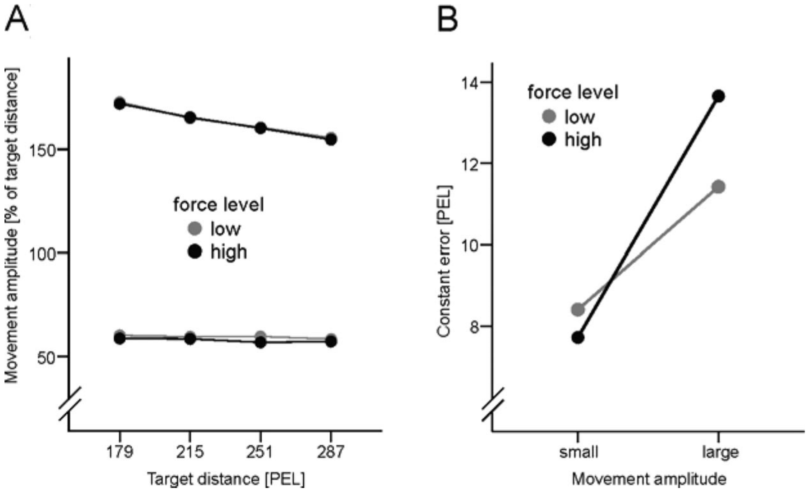

Figure 5. Main results of Experiment 3. Movement amplitude in % of target distance (A) and mean constant error as a function of the movement instruction and the level of force device (B).

ably due to the blockwise manipulation of movement amplitude. Second, and more important, the observed interaction between movement instruction and force level reveals that when motor planning parameters change trial by trial, the effort of an upcoming motor act affects perception of near space in addition to other variables relating to planning a movement. In particular, when movement extent and environmental forces change trial by trial and thus effectively affect perception, the modulation of distance perception might comply with the physical laws of mechanics. That is, an increase in external force in movements of large amplitude results in a stronger increase in overestimation of distances than in movements of relatively small amplitude, because mechanical work possibly underlying the subjective sense of effort changes nonproportionally in movements of small versus large amplitude when a constant amount of external force is applied to a moving joint.

General Discussion

The main purpose of the present study was to examine how anticipated movement costs affect perception of distances in reaching space. In particular, we aimed to demonstrate that the planning of goal-directed hand movements causes the same spatial location to appear as further away if movement effort increases. The results of three experiments suggest that this is indeed the case, at least under certain conditions.

Movement costs differed by the variation of required movement extent and of external force acting opposite of the direction of the hand movement. In Experiment 1, the level of external force remained constant within one block of trials, whereas the instructed movement extent varied trial by trial. The results indicated that participants overestimated distances more strongly when movements of relatively large amplitude had to be performed. A nonsignificant trend toward stronger overestimation with an increase in force level was also observed. Because an effect of movement extent was present only when movement instructions changed from one trial to the next, we hypothesized that the manipulation of external force was not effective due it's blockwise variation. The results of Experiment 2, in which external force could change trialwise, supported this hypothesis. We now observed a significant effect of external force on distance perception. In Experiment 3, instructed movement extent as well as external force changed within one block of trials. An interaction between both factors was observed. Participants overestimated distances more when instructed movement amplitude increased. In addition, the tendency to overestimate a given distance was more pronounced when high force level was applied, but only for the movements of a relatively large amplitude.

These results extend previous research by at least two aspects. First, the mere fact that increasing the difficulty of a planned hand movement produces changes in visual distance judgments suggests

Table 3
Mean Perceptual Error Scores (PEL) in Each Experimental Condition of Experiment 3

Target distance (PEL)	179		215		251		287	
Force level	Low	High	Low	High	Low	High	Low	High
Movement amplitude								
Small	10.42 (17.48)	10.05 (17.27)	9.26 (22.26)	8.21 (21.46)	6.53 (24.73)	6.58 (16.41)	7.42 (26.58)	6.05 (25.06)
Large	13.58 (19.57)	12.42 (17.79)	10.74 (21.22)	14.16 (20.62)	11.05 (21.29)	12.84 (19.95)	10.32 (25.35)	15.21 (28.35)

Note. Standard deviations are shown in parantheses.

that effort-related modulations of perception exist in reaching space. Conceivably, such a movement cost's dependent plasticity is based on mechanisms similar to those assumed for effort-related modulations in extrapersonal space (e.g., Bhalla & Proffitt, 1999). In particular, we suppose that perception might be biased by several variables that can be assumed to be an integral part of action planning. (See also sections Introduction and Experiment 1.) If so, then planning of actions including evaluation of movement costs can be assumed to affect perception across a variety of action types and spaces. In this rather abstract view, the effects observed in the present study would be equivalent to related phenomena observed in extrapersonal space. Admittedly, however, the physiological burdens in reaching space are generally smaller than in extrapersonal space (i.e., in terms of energetic costs, but see Rosenbaum, 2008), which might suggest that perception in the former is influenced to a lesser extent than the latter. For instance, an increase in walking effort up a 30-degree hill may be expected to have a stronger impact on perception than an increase in motor effort of a hand moving forward. Addressing this issue requires studies in which possible effort-related modulations of perception are simultaneously examined in near and far spaces.

Regardless of this possible relation of motor influences on perception in different spaces, the results speak against a strict dissociation between action planning and conscious visual perception in hand movements (cf. also e.g., Janczyk & Kunde, 2010). Instead, it suggests that the current content of an action plan can affect visual perception. Vishton et al. (2007) came to a similar conclusion, analyzing choice behavior before grasping and verbal reports in a setup in which participants had to decide between two identical disks surrounded by small- and large-circle arrays (Ebbinghaus illusion). The authors observed that the amount of the illusion was not only reduced for grasping behavior, but also for choices preceding grasping movements. They suggested that many previously reported results, which were interpreted as evidence for two separate streams of visual processing, "could be produced by a single system with two different modes of processing" (Vishton et al., 2007). That is, the type of intention (or of current motor plan) may alter not only the way near space actions are planned and executed, but also the way we perceive stimuli to which actions are related (see also Bekkering & Neggers, 2002; Gutteling et al., 2011).

Second, motor variables seem to make a significant contribution to the current content of the experienced perception, especially if motor-planning processes change with respect to the preceding motor act (results of trial analyses in Experiments 1 and 2). This intriguing aspect of the data highlights that short-term variation in motor planning, rather than enduring "motor potential," are responsible for motor effects on perception. In other words, the perceived layout may remain constant as long as a current motor plan (or the content of the current intention) does not change. This could imply that a hill does not generally appear steeper if one is wearing a heavy backpack, but only if one is wearing a heavy backpack after one was wearing a light backpack (or after one did not wear any backpacks). Analogously, using a tool could have an effect on perception of egocentric distances only if tools are alternately used with "no-tool conditions." Also, athletes could see a goal as being larger/smaller only if performance can vary (i.e., be "good" and "poor") with a certain time interval. This post hoc account is, of course, speculative and has to be substantiated by further research. Nevertheless, it appears to be plausible and rather adaptive. As suggested by Proffitt (2006, see also Witt, 2011b), perception signals the opportunities and the costs associated with action. For instance, a tendency to overestimate the slant of a hill while wearing a heavy backpack may help the walker to decide how fast to walk. However, if there are no changes in behavioral relevance of external characteristics there may be no need to change the current view on the environment.

From a more pragmatic point of view, this finding may also indicate that participants did not pay much attention to motor planning during distance estimates when movement characteristics did not change. As a result, the assumed interaction between motor planning and distance perception did not occur.

These conclusions should, of course, be considered with caution due to some possible caveats, which limit validity and generalization of the results. For instance, one striking result was that the impact of movement instruction on distance judgments differed substantially between Experiment 1 and Experiment 2. This outcome is surprising at first glance, given the fact that both experiments were different only with respect to whether movement instruction could change or remain constant within one block of trials. In particular, the direction of the effect found in Experiment 2, namely an increase in judgments with a decrease in movement amplitude (i.e., "contrast effect"), was not predicted. One possible origin of this bias may be derived from the adaptation level theory (ALT, Helson, 1964), which posits that subjective judgments depend on the relationship between the physical value of a current ("focal") stimulus and the physical value of the current "adaptation level," a type of reference point with respect to which subjective judgments are made. An adaptation level is considered as a weighted geometric mean of all stimuli "impinging" upon the organism over a time interval, including the so called "contextual" stimuli. In Experiment 2, in which movement instruction was varied blockwise, one can assume that the adaptation level shifted toward a lower value in the 50% condition because the averaged movement amplitude (contextual stimuli) was shorter than the averaged target distance (focal stimuli). In contrast, in the 150% condition, the averaged movement amplitude is larger than the averaged target distance. Accordingly, the adaptation level may be assumed to shift toward a higher value. Thus, the contrast effect observed in Experiment 2 may be explained by differences in the reference point with respect to which individual estimates were made. This view would imply that there is a dimensional overlap between movement extent and distance judgments and would thus further substantiate the assumed relation between movement planning and distance perception. The results of trialwise manipulations are not ambiguous with respect to such a context modulation, because according to the ALT, the adaptation level must be identical to both movement instruction conditions.

Another possible caveat is related to the fact that the target-distance factor did not interact with variations of force or of instructed movement amplitude. Taking an effect of anticipated effort for granted, such an interaction, at least with the external force manipulation, can be predicted (see also Experiment 3). We assume that the lack of this result may be due to a small distance variation across the four target conditions (the distance between the closest and the most distant target was 108 PEL only). Movement instruction, in contrast, required amplitude differences between 50% and 150% conditions in the range between 179 and 287

PEL. Also, the external force manipulation was associated with "potential" distance differences lying far beyond these values (i.e., the difference in effort between the high and the low levels may be assumed to correspond to a movement distance of several hundred PEL). Thus, an assumed interdependence between target distances and variations in movement extent and effort may have been undetectable due a low signal-to-noise ratio.

To demonstrate an effect of effort variables on perception, we used a somewhat artificial experimental setting: Though movement planning was related to an external location that had to be judged, the movement end position did not correspond with this location. Accordingly, possible interactions of motor variables, such as movement extent or movement costs, with cognitive operations of, for example, magnitude (i.e., mental increasing and decreasing of distance) cannot ultimately be ruled out. The results of our previous study (Kirsch et al., 2012) in which we observed an effect of numerical magnitude on distance judgments (larger numbers were associated with greater distance estimates) suggests this possibility.

Keeping these caveats in mind, we consider the overall results of the present study as evidence for a motor-planning hypothesis derived from recent empirical and theoretical work on embodied perception. In essence, we assume that the current content of a subjectively experienced perceptual event (perception) is the result of early sensory processing (sensation) enriched or rescaled by motor variables that are a part of a current motor plan. The precursors of this hypothesis can be found in the recent works of Dennis Proffitt and coworkers (e.g., Proffitt, 2008; Witt, 2011a, 2011b; Witt et al., 2010) as well as in some earlier motor theories of perception (see, e.g., Scheerer, 1984 and Viviani, 2002 for historical reviews and Van der Heijden, Müsseler, & Bridgeman, 1999 for a more recent example). The basic idea behind these approaches is that the perceiver perceives the external world in terms of his or her real or potential action. Our hypothesis extends and makes these ideas more precise, in that we basically assume that the external world is perceived in terms of the content of a current motor plan.

To conclude, we consider the present study to be an attempt to further refine the theoretical questions about the precise nature of perceptual-motor interactions. Our results suggest that anticipated movement costs affect visual perception of distances in reachable space. Thus, not only near lovers can sometimes appear far away, but also simple objects in grasping space can appear, at least a bit further away, if perceivers plan to do something wearisome.

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