The uphill battle for action-specific perception

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Abstract

The action-specific account of perception states that a perceiver's ability to act influences the perception of the environment. For example, participants tend to perceive distances as farther when presented up hills than on the flat ground. This tendency is known as the distance-on-hill effect. However, there is debate as to whether these types of effects are truly perceptual. Critics of the action-specific account of perception claim that the effects could be due to participants guessing the hypothesis and trying to comply with the experimental demands. The present study aims to explore the distance-on-hill effect and determine whether it is truly perceptual or whether past results were due to response bias. Participants judged the relative distance to targets on a hill and the flat ground. We found the distance-on-hill effect in virtual reality using a visual matching task. The distance-on-hill effect persisted even when participants were given explicit feedback about their estimates. We also found that the effect went away, as predicted by a perceptual explanation, when participants had to match the distance between two cones that were both on hills. These results offer important steps toward the painstaking task of determining whether action's effect on perception is truly perceptual.

Keywords Perception and action · Scene Perception · Embodied perception

Recent research has found that people perceive the spatial layout of their environment in a way that relates to their ability to act. Perceptual experiences of spatial properties like distance, slant, and size can be modulated by factors such as the amount of energy a distance would take to walk or how difficult a task would be to perform (e.g., Bhalla & Proffitt, 1999). The idea that ability to act has an influence over one's perception is known as the action-specific account of perception (Proffitt, 2006; Witt, 2011, 2017). For example, softball players who had higher batting averages than others for the game or games played that night estimated the ball as larger (Witt & Proffitt, 2005). As another example, when playing a modified version of the computer game Pong, participants viewed the ball as moving faster when they played with a smaller paddle that was less effective at blocking the ball than when they played with a larger one (Witt & Sugovic, 2010; Witt, Sugovic, & Taylor, 2012; Witt, Tenhundfeld, & Tymoski, 2017). Pedestrians who were older, overweight, or had other

difficulties with taking the stairs perceived them as steeper (Eves, Thorpe, Lewis, & Taylor-Covill, 2014).

Action-specific perception and distance

Action-specific effects on the perception of distance has been studied in a variety of ways. Physical factors such as weight and health can influence perception of distance. For example, patients who experienced chronic pain when walking judged a distance as farther than someone who experienced no pain when walking judged it (Witt et al., 2008). Participants who weighed more than others also judged distances as farther (Sugovic, Turk, & Witt, 2016). Both of these studies revealed an influence of long-standing bodily characteristics on perceived distance. Distance perception can also be influenced by temporary physical manipulations as well. Participants who were wearing a heavy backpack estimated distances as being farther than did those with no backpack on (Proffitt, Stefanucci, Banton, & Epstein, 2003), and participants wearing ankle weights estimated gaps as farther than did participants not wearing the weights (Lessard, Linkenauger, & Proffitt, 2009). This suggests that distance perception is influenced by the energetic costs associated with performing a given action.

Another action-specific effect on perception was found when participants judged distances on hills to be farther than

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distances on flat planes, presumably because walking up the distance on a hill would have more energetic costs than would the flat plane (Stefanucci, Proffitt, Banton, & Epstein, 2005). We will refer to this phenomenon as the *distance-on-hill effect*. The distance-on-hill effect was apparent in both outdoor natural environments and virtual reality. In the original studies (Stefanucci et al., 2005), participants estimated distances via verbal report. For each target, they would estimate the distance to the target in feet and inches. Targets presented up a hill were estimated as being farther away than targets on flat ground were. This pattern emerged for both real environments and virtual environments.

The distance-on-hill effect persists even when using different techniques to measure distance perception (Tenhundfeld & Witt, 2017). One way to measure perceived distance is to use a blind walking task for which participants view a target, close their eyes, and attempt to walk to the target while blindfolded (Loomis, Silva, Fujita, & Fukusima, 1992). This is an effective measure because participants are quite accurate, and the task does not require translating perception into an explicit magnitude judgment, which is a challenging task. Participants were shown a cone placed at a target distance on either the flat ground or a hill. They were then blindfolded and told to walk the equivalent distance along the flat ground. It was important to have them walk along the flat ground rather than walk to the target itself so that any differences in distance walked could not be attributed to walking up a hill versus on flat ground. Participants walked farther when the distance shown was on a hill as opposed to the equivalent distance on a flat surface (Tenhundfeld & Witt, 2017). In another experiment, participants engaged in a visual matching task. They saw a target cone on a hill as well as a reference cone on a flat surface and instructed a researcher to move the cone on the flat ground until the participant perceived distance to each cone to be equidistant. Participants positioned the flat cone to be farther away than the hill cone, suggesting the hill cone appeared to be farther (Tenhundfeld & Witt, 2017). The convergence across a variety of measures is consistent with a perceptual interpretation of the distance-on-hill effect.

Critiques on action-specific perception effects

The action-specific account of perception has been criticized for making claims that action influences perception, rather than effects on nonperceptual processes instead. Given that it is impossible to measure perception directly, researchers must infer effects on perception based on observable behaviors. But any observed effects could be the result of differences in perception or differences in any of the other processes involved in generating a behavioral response.

Firestone and Scholl (2016) determined a framework for evaluating action-specific effects on perception by outlining six pitfalls that can instead account for such effects being

found in previous experiments. One of the primary pitfalls is the idea that the results could be due to response bias rather than true perceptual effects. For example, Durgin et al. (2009) challenged Bhalla and Proffitt's (1999) claim that wearing heavy backpacks causes participants to perceive a hill as being steeper. They suggest that participants wearing a backpack report the hill as being steeper not because it looks steeper but because participants attempted to comply with experimental demands. According to Durgin et al. (2009), wearing a backpack induces a demand characteristic such that participants could infer the experimental hypothesis and adjusted their responses accordingly. They supported their claims with evidence that showed that when participants were given an alternative explanation for why they were wearing a backpack, they did not guess the hill to be any steeper than those participants who did not wear a backpack.

More generally, similar critiques have been made regarding all action-specific perception effects. Firestone and Scholl (2016) have suggested that one way to assess whether this response bias account could explain action-specific effects is to interview participants after a task to assess whether they were able to guess the experiment's hypothesis. If only participants who could correctly guess the study's purpose showed the effect of action, this would be evidence for a response bias account.

Another pitfall is that the current literature on action-specific perception has overly confirmatory findings (Firestone & Scholl, 2016). This means that while it is important to show the effects where they should be found, it is also important to show that such effects are not present where they should not be found. Firestone and Scholl recommended evaluating effects using an "El Greco" strategy. This strategy gets its name from the painter, El Greco, who is famous for painting figures who were unrealistically long and slender. Historians originally hypothesized that he had a visual problem, in which he saw the world in such an elongated way. However, it became apparent that if he really saw the world in such a way, he would also see the canvas and the background in such a way, which would cancel out the effects of his elongated sight. Therefore, if he saw the world as elongated, and he saw the canvas as elongated, he would paint things as he saw them in reference to the elongated canvas and end up with an image depicting normal-sized people (Firestone & Scholl, 2014).

Similar logic has been used to evaluate studies on action-specific effects. If a perceptual bias was truly present for the target object, it should also be present for the comparison object (just like any bias in El Greco's vision for the scene would also be present in his vision for the canvas). Thus, if an effect is perceptual, then the effect on the comparison object would be the same as the effect on the target object, and no significant difference would emerge. In contrast, if an effect does emerge, then it suggests that the perception of the objects are the same and the difference in the response is due to response bias.

An example of how Firestone and Scholl have applied the El Greco strategy to action-specific effects is as follows. Stefanucci and Geuss (2009) found that participants who held a large rod rated doorways as narrower, hypothesizing that this was because the aperture was now less walkable with a long rod. Ratings were taken by having participants manipulate a tape measure to the length of the doorway. Firestone and Scholl (2014) tested this proposed effect using the El Greco strategy by having participants complete a similar experiment, but instead of using a tape measure, participants manipulated another aperture with the goal of making it identical to the first. If the rod made the first aperture look narrower, it should also make the second aperture look narrower. Therefore, the effect should cancel each other out, and participants should make the apertures equal sizes. However, participants made the second aperture significantly smaller than the first. This gives evidence that participants were not really seeing apertures as narrower due to the pole, which gives way for alternative explanations such as response bias.

The El Greco strategy could be similarly applied to the distance-on-hill effect. Rather than have the comparison object be on the flat ground, both objects could be on identical hills. If a target placed up a hill genuinely looks farther away than a target placed on flat ground, then this visual effect would be present for both the target object and comparison object. Participants would see the target object as being farther than the true distance. However, when manipulating the comparison object that is also on a hill, participants would also see the comparison object as being farther than it truly is. These effects would cancel each other out. Thus, participants should accurately position the comparison object. In contrast, if the effect is due to response bias, then participants should move the comparison object farther away than the target object, in an effort to give the biased response that the target object looks farther away.

Given the criticism that action-specific effects might not be due to perceptual differences, it is necessary to critically and systematically evaluate whether the distance-on-hill effect reflects genuine differences in perception, or whether it is due to one of the pitfalls instead.

In defense of action-specific perception

One strategy for differentiating whether effects are due to genuine differences in perception versus postperceptual processes is to examine convergence across different types of responses (Foley, 1977). If an effect is only found in verbal estimates, but not in other kinds of measures (like visual matching), this would be consistent with a postperceptual account rather than a perceptual effect. That the distance-on-hill effect is found using a variety of measures, including verbal estimates, visual matching, and blind walking, is consistent

with a perceptual explanation (Tenhundfeld & Witt, 2017). However, while convergence is a necessary condition for a perceptual explanation, it is certainly not sufficient.

Another necessary condition for a perceptual explanation is that the effect of action on perception should be apparent regardless of whether participants can infer the purpose of the study. Tenhundfeld and Witt (2017) gave participants a survey to assess whether participants could intuit the direction of the distance-on-hill effect. Participants viewed a drawing of a person standing between two equidistant objects on a hill and flat plane and were given a multiple-choice question with three options about how the viewer would perceive the objects. Their choices were that the object on the hill would appear farther, the object on the flat plane would appear farther, or the objects would appear equidistant. Only 30% of surveyed participants inferred the direction of the distance-on-hill effect, and 64% inferred the opposite direction (Tenhundfeld & Witt, 2017). Thus, it is difficult to explain the distance-on-hill effect by appealing to a response bias explanation given that participants' inferences would have produced an effect in the opposite direction. However, response bias can be tricky to rule out completely (Philbeck & Witt, 2015).

Reliable tasks needed

Another criticism of action-specific effects is that a perceptual mechanism has not been adequately proven (Firestone, 2013). To determine a mechanism, it is necessary to have tasks that are both replicable and reliable. Cognitive tasks tend to be very replicable (meaning that the effect emerges at the group level most of the time), but not particularly reliable (Hedge, Powell, & Sumner, 2018). To be reliable, the task needs to have good intrasubject reliability, which means that a participant's score on, for example, even trials should correlate with their score on odd trials. A task with both replicability and reliability would be a huge asset for determining the underlying mechanisms because we could leverage individual differences, or "nature's manipulation," to find shared and unique processes (Wilmer, 2008). A robust, reliable task could also be used to determine whether certain individuals do not experience action-specific effects (as suggested by some personal experiences of some scientists; e.g., Loomis, 2016) while others do (as suggested by quotes from athletes; e.g., Witt & Proffitt, 2005; Witt & Sugovic, 2010).

It is difficult for a task to be both replicable and reliable (Hedge et al., 2018). A notable exception is the distance-on-hill effect, but only as assessed with a visual matching task (Tenhundfeld & Witt, 2017). However, this version of the task has only been performed in an outdoor environment, which relies on good weather and having access to hills. Here, we explored the effect in a virtual environment to determine

whether we could develop a version of the task that achieves both replicability and reliability. This methodological step is important for future studies to uncover the underlying mechanism.

Overview of present studies

Previous studies have shown that the distance-on-hill effect is present in various circumstances in both real physical hills and virtual-reality environments (e.g., Stefanucci et al., 2005). However, the question remains as to whether these effects are truly perceptual. The present studies seek to answer this question through the process of systematically ruling out various alternative explanations for the distance-on-hill effect, as has been done with other action-specific effects. We addressed the pitfalls outlined by Firestone and Scholl (2016), as well as determined reliability of the tasks in virtual environments.

To address concerns regarding whether these effects are perceptual, we first attempted to replicate the visual matching methodology that had previously proven to be reliable outside, in a virtual environment. Second, we evaluated the role of judgment-based processes in the distances-on-hill effect by adding explicit feedback. After each estimate, participants were told whether their judgments were too far or too close. This feedback should create an expectation that participants are supposed to answer as accurately as possible, rather than to answer in a way that would conform with the research hypothesis (King, Tenhundfeld, & Witt, 2017). By giving participants immediate and repeated feedback, the feedback can influence the participant's response strategy to emphasize accuracy based on physical distance, rather than on subjective feelings of difficulty or another factor that could be guiding responses (cf. Firestone & Scholl, 2016). Third, we evaluated an issue with the methodologies of the first two experiments by controlling for a potential confounding factor. Fourth, we employed the “El Greco” strategy to further explore a potential role for response bias.

Experiment 1: Distance-on-hill effect in virtual reality

The purpose of this study was to replicate the distance-on-hill effect using the visual matching task, but do the experiment in virtual reality instead of the real world. This would make the methodology more accessible to more researchers given the current availability of inexpensive virtual reality.

Method

Participants Twenty-seven volunteers participated in exchange for course credit.

Stimuli and apparatus All stimuli were presented in an Oculus Rift DK2 head-mounted display (HMD) with a resolution of 960×1080 pixels per eye, and a field of vision (FOV) of 100 degrees. A custom program made in Unity presented a grassy environment in virtual reality (VR) in the HMD. The HMD tracked rotational head movements in order to update the participants' view of the scene, but head movements were not recorded, and translational movements were not recorded nor had any effect on the visual scene. Participants stood in one place during the experience, and rotated only, so translation was not a component of the experiment.

The Unity program depicted a grassy field with a hill on one side. A bench was placed on the hill to help cue participants to the slope of the hill, which was always 20 degrees. The slant of the hill was not altered, as the intention of this experiment was not to determine the effects of different hill slants on distance judgments; rather, the intention was to replicate previous distance-on-hill findings in VR. Two cones were presented. The cones were yellow cylinders that were 1 m tall and had a diameter of 0.5 m. One cone was on the hill directly in front of the participant's initial view; the other cone was on the flat ground 90° to the right of the participant. Both were presented at the start of each trial (see Fig. 1). One cone was static (the target cone) and one could be moved (the comparison cone). The comparison cone could be moved either closer to or farther from the participant by scrolling the mouse wheel. Each change in position displaced the comparison cone by 10 cm.

Procedure After providing informed consent, participants were asked to put on the HMD, which was adjusted to fit each participant. Their position in the virtual world was at the foot of the virtual hill. Each participant stood on the same marked spot on the floor and could rotate to see each cone. Participants could rotate to see each cone, but they could not translate (i.e., move) through the virtual environment.

At the start of each trial, both cones were presented. For one block of trials, the target cone was on the hill and the comparison cone was on the flat ground, and vice versa for the other block of trials. The target cone was placed at 6, 8, 10, or 12 meters (m) from the participant, and the comparison cone was placed at 2 m or 16 m. Participants were instructed to move the comparison cone (by scrolling the mouse wheel) until the egocentric distance to both the target and comparison cones were equal. Once the comparison cone was moved to a position that the participant perceived to be egocentrically equal in distance to the target cone, the participant would click the mouse button to record the data and to start the next trial. Participants completed two blocks of 24 total trials: six for each of the four target cone distances (three with the comparison cone starting close and three with the comparison cone starting far). Order within block was randomized.

Fig. 1 Screen capture of the virtual environment. In this scene, the comparison cone is on the hill (left panel) and the target cone is on the flat ground to the right of the hill (right panel)

Data analysis Data for all experiments were preprocessed as follows. First, all trials for which the final matched distance of the comparison cone matched the initial distance to the comparison cone were removed. The idea was that these were trials for which participants might have accidentally hit the wrong button without adjusting the comparison cone first. It is possible that some of these trials were trials for which participants did make adjustments, but even if they had, these trials would have been excluded as outliers anyway. These trials comprised less than 1% of the data. Next, we labeled responses on individual trials as outliers if they were more than 1.5 times the interquartile range (IQR) for each target distance. We then computed the proportion of trials considered as outliers for each participant, and plotted these using box plots. Participants with proportion of trials that were at least 1.5 times the IQR for the group were excluded altogether. In addition, for the remaining participants, any individual trials that were considered outliers were excluded as well.

Data were analyzed using linear mixed models in R (R Core Team, 2017) using packages LME4 and LMERTTEST (Bates, Machler, Bolker, & Walker, 2015; Kuznetsova, Brockhoff, & Christensen, 2017). For all models, decisions were made based on whether to include random slopes for various within-subjects factors or only the random intercepts based on which model fit the data best.

Results and discussion

Data were preprocessed using the three steps described above. Final and initial comparison distance matched on less than 1% of all trials. Five participants were identified as outliers because their mean proportion of outlier trials was beyond 1.5 times the IQR and were excluded. Remaining individual trials that had been labeled as outliers were also excluded. This comprised less than 0.5% of the remaining data.

The data were submitted to a linear mixed model. The dependent measure was matched distance. The within-subjects factors were terrain (coded as 1 for hill and 0 for flat), target distance (centered by subtracting mean target distance), and their interaction. Subject was included as a random factor. Terrain significantly influenced matched distance, $t = 2.33$, $p = .029$, estimate = 0.59 m, $SE = 0.25$ m. Participants estimated the cone on the hill to be farther than the cone on the flat ground. Target distance significantly influenced matched distance, $t = 34.50$, $p < .001$, estimate = 0.80 m, $SE = 0.02$ m. As target distance increased, matched distance also increased. However, the coefficient was less than 1, suggesting that participants did not position the comparison cone as far away as target distance increased. The interaction was significant, $t = 7.79$, $p < .001$, estimate = 0.19 m, $SE = 0.02$ m. As target distance increased, the cone on the hill looked even farther than the cone on the flat ground (see Fig. 2). This result reveals the distance-on-hill effect in a virtual environment using a visual matching measure. Before interpreting this result, we first attempted replicate it.

Experiment 2: Replication of the distance-on-hill effect in virtual reality

Experiment 2 was a direct replication of experiment 1. Cognitive psychology is currently facing what many would call a replication crisis (Aarts et al., 2015). However, many of the studies replicated in the original article were either underpowered or had the methods significantly changed in some way (Gilbert, King, Pettigrew, & Wilson, 2016). With this in mind, we chose to include a true and direct replication with similar power to the first experiment before going forward with the theory.

Fig. 2 Mean matched distance is plotted as a function of target distance and target terrain (hill or flat) for Experiment 1. Lines represent linear regressions, and error bars are 1 *SEM* calculated within subjects. The error bars are approximately the same size as the symbols. (Color figure online)

Method

Twenty-eight volunteers participated in exchange for course credit. Everything else was identical to Experiment 1.

Results and discussion

During preprocessing, less than 0.3% of the data were excluded because the matched distance was the same as the initial comparison distance. Five participants were identified as outliers and excluded because their mean proportion of outlier trials was beyond 1.5 times the IQR. Finally, individual trials that had been labeled as outliers were also excluded (less than 0.8% of the remaining data).

The data were analyzed as before using a linear mixed model. Terrain significantly influenced matched distance, $t = 2.78$, $p = .011$, estimate = 0.65 m, $SE = 0.23$ m. Participants estimated the cone on the hill as farther than the cone on the flat ground (see Fig. 3). Target distance influenced matched distance, $t = 39.85$, $p < .001$, estimate = 0.83 m, $SE = 0.02$ m. The interaction was significant, $t = 7.69$, $p < .001$, estimate = 0.19 m, $SE = 0.02$ m. Thus, the data closely match the data from Experiment 1.

Previously, the distance-on-hill effect has been shown in virtual reality using verbal estimates (Stefanucci et al., 2005) and with real hills using visual matching measures (Tenhundfeld & Witt, 2017). Combining the virtual environment with the visual matching is important because virtual reality permits faster data collection and more control over the environment, and the visual matching task is the only measure thus studied that has good intrasubject reliability (Tenhundfeld & Witt, 2017). Neither verbal estimates nor blind-walking measures showed intrasubject reliability.

Fig. 3 Mean matched distance is plotted as a function of target distance and target terrain (hill or flat) for Experiment 2. Lines represent linear regressions, and error bars are 1 *SEM* calculated within subjects. The error bars are approximately the same size as the symbols. (Color figure online)

Reliability is critical for developing a task that can be used to ask questions beyond mere demonstrations such as whether certain individuals are more prone to these effects or regarding the mechanisms underlying these effects.

To explore whether the current task had good reliability, we combined the data from Experiments 1 and 2. To compute split-half reliabilities, each participant's data was divided into two parts: their estimates on the two outermost distances (6 m and 12 m) compared with their estimates on the two middle distances (8 m and 10 m). This division was chosen so that the mean target distance was the same for both halves. For each half, the mean distance-on-hill score was calculated by taking the difference between the means for the matched distance for the hill and flat conditions. A larger distance-on-hill score corresponds to estimating targets as being farther up the hill than on flat ground. Participants each had two distance-on-hill scores: one for the outermost distances, and one for the middle distances. The correlation between the two scores was $r = .87$, $p < .001$ (see Fig. 4). The Spearman–Brown prophecy coefficient was .93, indicating that the task had very good reliability. Currently, this is the only known lab-based task that can reliably measure individual differences in an action-specific effect.

Experiment 3: Explicit feedback on perceptual judgments

One way to eliminate response bias and judgement-based effects is to provide explicit feedback about the accuracy of the perceptual responses (King et al., 2017). The feedback communicates to the participant that the task is to be as accurate as possible and to accurately report the

Fig. 4 The distance-on-hill effect calculated for outer distances (6 m and 12 m) is plotted as a function of the distance-on-hill effect calculated for the middle distances (8 m and 10 m). Each point represents one participant in Experiments 1 and 2. The line corresponds to the linear regression

specific factor of interest. Estimating distance is difficult, so some participants might estimate how hard the distance *feels*, rather than the perceptual experience of the distance (Fajen & Phillips, 2012; Firestone & Scholl, 2016; Philbeck & Witt, 2015). If so, this would lead to the distance-on-hill effect even if participants perceived the distances to be the same. Similarly, the distance-on-hill effect would emerge if participants biased their responses to comply with expectations that the hill cone should appear farther. To empirically evaluate both possibilities, feedback on the perceptual matching task was provided on each trial. If the effect is perceptual, then the feedback should not reduce the effect, whereas it should reduce any effects due to response bias or judgment-based effects, as has been shown previously (King et al., 2017).

Method

Forty-five volunteers participated in exchange for course credit. The materials were identical to those in Experiments 1 and 2. The procedure differed only insofar as explicit feedback about participants' accuracy in visually matching the distances was provided after each trial. Feedback was floating text in the center of the display and was given on trials for which the comparison cone position was closer or farther than the target cone by at least 10 cm. When the comparison cone was positioned too close, the feedback stated, "Your estimate was too close." When the comparison cone was positioned too far, the feedback stated, "Your estimate was too far."

Results and discussion

One participant did not complete the experiment, and their partial data was not included in the analysis. During preprocessing, 1.4% of the data were excluded because the matched distance was the same as the initial comparison distance. Six participants were identified as outliers because they had a mean proportion of outlier trials beyond 1.5 times the IQR. Individual trials that had been labeled as outliers were excluded. This comprised 1.5% of the remaining data.

The data were submitted to a linear mixed model. The dependent factor was matched distance. The independent factors were target distance (which was centered by subtracting mean target distance), terrain (coded as flat = 0 and hill = 1), and their interaction. Subject was included as a random factor, and random slopes were included for the within-subjects factors. Terrain significantly influenced matched distance, $t = 3.47$, $p = .001$, estimate = 0.33 m, $SE = 0.09$ m. Participants estimated the distance on the hill to be .33 m farther than the distance on the flat ground. Thus, even with feedback on their perceptual judgments, participants continued to show the distance-on-hill effect. Target distance significantly influenced matched distance, $t = 47.53$, $p < .001$, estimate = 0.80 m, $SE = 0.02$ m. As in the other experiments, the coefficient was less than 1, suggesting a bias to move the comparison cone closer as distance increased. The interaction between terrain and target distance was significant, $t = 12.62$, $p < .001$, estimate = 0.26 m, $SE = 0.02$ m. For every meter increase in target distance, the distance-on-hill effect increased by 0.26 m (see Fig. 5).

Even with explicit feedback about the matched responses, the distance-on-hill effect emerged. This is consistent with a perceptual explanation. Assuming the feedback was sufficient

Fig. 5 Mean matched distance is plotted as a function of target distance and target terrain (hill or flat) for Experiment 3. Lines represent linear regressions, and error bars are 1 SEM calculated within subjects. The error bars are smaller than the symbols. (Color figure online)

to minimize or even eliminate any demand characteristics associated with the task, the current results are inconsistent with a response bias explanation.

Experiment 4: Potential confound of the bench

For each of the previous experiments, a bench was placed on the hill, but not on the flat ground. In hindsight, the bench is potentially problematic because it could affect perceived distance to the cone. Thus, we replicated the studies using a hill without a bench.

Method

Participants Fifty-five participants were recruited to participate in the study in exchange for course credit. Three participants did not start the fourth block of trials, and one participant only completed approximately half of the fourth block, so they were excluded from analyses.

Stimuli and apparatus The stimuli and apparatus were identical to those used in Experiments 1–2, except that participants completed four blocks (instead of two). Two blocks were identical to those in Experiments 1–2, and the other two blocks were the same, except there was no bench present on the hill.

Procedure The procedure was identical to that of Experiments 1–2, with the addition of two blocks per participant utilizing the hill scene without the bench; one block in which the target cone appeared on the flat ground, one in which it appeared on the hill. Thus, a total of 96 trials were completed for each participant (4 target cone distances $\times$ 2 comparison cone distances $\times$ 3 trials $\times$ 2 initial comparison cone locations $\times$ 2 bench conditions). Participants completed two blocks with the bench followed by two blocks with no bench or vice versa. Order of target cone placement (hill vs. flat) was randomized across participants. One participant did a different order and was included in the initial analyses but eliminated when we analyzed only the first two blocks.

Results and discussion

Data were preprocessed as before. The matched distance was the same as the initial comparison distance on 0.6% of trials, and these trials were excluded. Four participants did not complete the task, and eight participants were identified as outliers for having mean proportion of outlier trials greater than 1.5 times the IQR. We also excluded individual trials for which the response was identified as an outlier, which was 1.1% of the remaining data.

The main research question was the extent to which the presence of the bench contributed to the measured distance-on-hill effect. The data were submitted to a linear mixed model. The dependent factor was final comparison distance. The independent factors were target distance (which was centered by subtracting mean target distance), terrain (coded as flat = 0 and hill = 1), and bench presence (coded as absent = 0 and present = 1). All interaction terms were included among these independent factors. The random effect was participant number, and random slopes for each factor were also included. The effect of target distance was significant, $t = 44.49$, $p < .001$, estimate = 0.82 m, $SE = 0.02$ m. The effect of terrain was not significant, $t = 1.07$, $p = .29$, estimate = 0.18 m, $SE = 0.17$ m. However, the interaction between terrain and distance was significant, $t = 8.85$, $p < .001$, estimate = .16 m, $SE = 0.02$ m (see Fig. 6). For every meter increase in target distance, the hill cone looked 0.16 m farther than the flat cone. The effect of the bench was not significant, $t = 0.75$, $p = .46$, estimate = 0.05 m, $SE = 0.06$ m. Critically, the interaction between bench and terrain was not significant, $t = 0.98$, $p = .33$, estimate = 0.05 m, $SE = 0.06$ m, and the interaction between bench, terrain, and target distance was also not significant, $t = 0.37$, $p = .71$, estimate < 0.01 m, $SE = 0.02$ m.

However, when we explored individual scores for the distance-on-hill effect, we noticed a bimodal distribution (see Fig. 7). When considering what could have caused this bimodal distribution, one obvious possibility related to order effects. Participants completed both blocks without the bench before the blocks with the bench, or vice versa. So the data were reanalyzed with order added as a between-subjects factor. There was a significant three-way interaction between terrain, bench, and order, $t = 3.12$, $p = .002$. To explore this

Fig. 6 Mean matched distance is plotted as a function of target distance, target terrain (hill or flat), and bench condition (bench in red; no bench in black) for Experiment 4. Lines represent linear regressions. The error bars, calculated within subjects, were approximately the same size as the symbols and were not plotted. (Color figure online)

Fig. 7 Frequency distribution of mean distance-on-hill effects, which were calculated by taking the mean estimate in the hill condition minus the mean estimate in the flat condition for Experiment 4. The vertical blue line is positioned at 0, which is the point of no distance-on-hill effect. (Color figure online)

interaction, the data from the first two blocks were submitted to a linear mixed model with matched distance as the dependent factor, terrain and target distance as within-subjects factors, bench as a between-subjects factor, and subject as a random effect.

The interaction between bench and terrain was not significant, $t = 1.35$, $p = .19$, estimate = 0.47 m, $SE = 0.35$ m, but the interaction between bench, terrain, and distance was significant, $t = 2.55$, $p = .011$, estimate = 0.19 m, $SE = 0.08$ m. The effect that targets up the hill looked farther than the targets on flat ground as distance increased was greater in the bench condition than in the no-bench condition (see Fig. 8). This raises the possibility that the explanation for why targets up the hill looked farther than on flat ground in Experiments 1–3 was not due to energetic costs associated with walking up the hill but rather with the fact that there was an object (the bench)

intersecting the distance. It is known that intersecting lines can increase perceived distance (Howe & Purves, 2005). To determine whether the bench accounted for the entire distance-on-hill effect, we analyzed the data just from the first two blocks for participants who did not have the bench. Although the effect of terrain was not significant, $t = 0.72$, $p = .48$, estimate = 0.17 m, $SE = 0.24$ m, the interaction between terrain and distance was significant, $t = 6.85$, $p < .001$, estimate = 0.39 m, $SE = 0.06$ m (see Fig. 8).

The current experiment indicates that the previous studies on the distance-on-hill effect in VR were not solely a function of the presence of a bench. This was a critical control experiment, and the results are consistent with the idea that distances up a hill look farther away because walking to them would require more energy. However, the bench seems to have contributed to the effect. This is surprising, as previous literature on virtual environments has stated that while in general participants tend to underestimate distances in virtual environments compared with real environments, there are no real differences in distance judgements based on quality of the environment (Thompson et al., 2004). In minimal environments with varying number of visual cues, participant's distance estimation did not improve when more simple cues were added into an otherwise minimal environment (Armbrüster, Wolter, Kühlen, Spijkers, & Fimm, 2008). Though the mechanism is unclear, the recommendation for future research on this effect is to use the virtual world that did not have the bench in order to reduce possible confounds.

Experiment 5: Matched terrain

According to the action-specific account of perception, targets on hills appear farther because it would take more energy to walk to them compared with targets on flat ground (Stefanucci et al., 2005; Tenhundfeld & Witt, 2017). An alternative

Fig. 8 Mean matched distance is plotted as a function of target distance and target terrain (hill or flat) for the first two blocks for Experiment 4. The left panels shows data for participants who had no bench, and the right panel shows data for participants who had a bench during the first

two blocks. Lines represent linear regressions, and error bars are 1 *SEM* calculated within subjects. The error bars are approximately the same size as the symbols. (Color figure online)

explanation is that participants report (but do not see) the targets on the hill as farther because they are complying with demand characteristics (cf. Durgin et al., 2009). One possible way to test these two explanations is to use an El Greco-style experiment (Firestone & Scholl, 2014). The idea is to evaluate an effect in a context for which any perceptual effect on the target object would be matched by a similar effect on the comparison object.

Applied to the distance-on-hill effect, both the target and comparison cones would be placed on hills (or both would be placed on flat ground), rather than one on each type of terrain. A perceptual explanation would predict null effects because the hill is hypothesized to increase perceived distance to both the target and the comparison when both are uphill. Consequently, participants would show no significant difference between placement of the target cone and comparison cone. In contrast, a response bias account would predict significant effects. According to the response bias account, participants anticipate that the cone up the hill is supposed to look farther and thus would estimate it as being farther even when the comparison cone is also on a hill. Therefore, participants would show a significant difference between the location of the comparison cone and the location of the target cone. This kind of pattern was found previously to support a response bias explanation for why a doorway would be reported as being narrower when one is holding a long object (Firestone & Scholl, 2014). More generally, this strategy falls under the first pitfall listed in the six-pitfall framework for Firestone and Scholl (2016). Here, we applied this strategy to the distance-on-hill effect.

Method

Participants Twenty-six volunteers participated in exchange for course credit.

Stimuli and apparatus Our virtual reality equipment was updated, so the stimuli were presented in an HTC Vive virtual reality HMD with a resolution of 1080×1200 pixels per eye, and FOV of 110 degrees. The stimuli were VR scenes in which two cones were presented, one static (the target cone) and one dynamic (the comparison cone, whose distance was controlled by the mouse wheel). The stimuli did not include the bench and were altered such that the target and comparison cones were presented 180 degrees from one another (i.e., one would be directly in front of the participant while the other would be directly behind). Additionally, for this experiment, two new VR scenes were added in which both the target and comparison cones were presented on hills (slanted in opposite directions such that the participant was standing in the valley between them) or both were presented on flat terrain. All hills in Experiment 5 had a slant of 20 degrees. In trials that had two hills or two flat planes, the plane on which the target cone and

the plane on which the comparison cone were presented were identical (e.g., in a “two hill” trial both hills would have the same slope and same appearance). This was to prevent any other factors from influencing one’s distance judgements, and distil the task to its most basic form: “Make the comparison stimulus identical to the target stimulus.” The stimuli were presented at 180 degrees from one another to keep all blocks consistent with the block in which the target and comparison cones were presented on hills.

Procedure The procedure was identical to that of Experiment 1, except that participants completed four blocks of trials. For two blocks, the two cones were on the same terrain (both on hills or both on flat ground) and for two blocks, one cone was on the hill and one cone was on the flat and which one was the target was varied across blocks. Participants were again instructed to move the comparison cone with the mouse wheel until the egocentric distance was equal to the egocentric distance to the target cone.

Results and discussion

Of the 26 participants, only 18 completed all four blocks in the allotted time and were included in the analysis. Data were preprocessed as before. Less than 0.8% of trials were excluded due to final matched distance being the same as the initial distance. Two participants were identified as outliers because their mean proportion of outlier trials was beyond 1.5 times the IQR. In addition, all other trials that were identified as outliers were removed (1.4% of the remaining data).

The two blocks for which the terrains were different served as a replication of the previous procedure to ensure that the distance-on-hill effect is still apparent in the HTC-Vive. The two blocks for which the terrains were identical served as the El Greco-style experiment in which the action-specific theory would predict null effects. Comparing those two groups of blocks allows us to examine scenarios where we expect significant effects against those where we expect null effects. Finding null effects when expected helps rule out the idea of results being due to demand characteristics.

The data were submitted to a linear mixed regression. The dependent factor was matched distance. The within-subject factors were terrain for the target cone (coded as 1 for hill and 0 for flat), terrain for the comparison cone (coded as 1 for same terrain and 0 for different terrain), distance (centered), and all the two-way and three-way interactions. Subject was entered as a random effect, and all random slopes were included. All effects were statistically significant (all p s $< .001$), so we will focus only on the critical effects. There was a significant interaction between target terrain and comparison terrain, $t = 14.15$, $p < .001$, estimate = 1.14 m, $SE = 0.08$ m. Target terrain had a bigger effect when the terrains were different than when they matched (see Fig. 9). This interaction

Fig. 9 Matched distance is plotted as a function of target distance, terrain, and whether the target and comparison cones were on different terrains (left) or the same terrain (e.g., both were on hills or both were on flat

ground; right) for Experiment 5. Lines represent linear regressions, and error bars are 1 *SEM* calculated within subjects. The error bars are approximately the same size as the symbols. (Color figure online)

was exaggerated as distance increased, $t = 7.46$, $p < .001$, estimate = 0.27 m, $SE = 0.04$ m.

To further explore these interactions, the data were analyzed separately when the terrains were different than when they were the same. When the terrains were different, terrain significantly influenced matched distance, $t = 3.65$, $p = .002$, estimate = 0.94 m, $SE = .26$ m. In other words, when the terrains were different, the distance-on-hill effect was observed, which replicates what was previously found. In addition, the interaction between terrain and distance was significant, $t = 8.65$, $p < .001$, estimate = 0.24 m, $SE = 0.03$ m. The distance-on-hill effect increased as distance increased. Target distance also influenced matched distance, $t = 22.50$, $p < .001$, estimate = 0.72 m, $SE = 0.03$ m. As the target distance increased, the matched distance increased as well, although not as much as it should have (as revealed by the estimate being less than 1).

The critical question is whether a similar difference between targets on the hill and targets on flat ground would be found when the terrains matched. According to a perceptual explanation, any effect on perceived distance to the target cone on the hill should be similar to the perceived distance to the comparison cone when it is on the hill. This would eliminate any effect related to the hill. Terrain had a marginally significant effect on matched distance, but importantly, the effect was in the opposite direction as would be predicted by a response bias account, $t = -2.00$, $p = .063$, estimate = -0.22 m, $SE = .11$ m. Participants positioned the comparison cone closer when both cones were on the hill than when both cones were on flat ground. Target distance significantly influenced matched distance, $t = 64.36$, $p < .001$, estimate = 0.90 m, $SE = .01$ m. The random slope for distance was excluded from this analysis because the model did not converge when it was included. The interaction between distance and terrain was not significant, $t = -1.48$, $p = .14$, estimate = -0.03 m, $SE = .02$ m.

That participants positioned the comparison cone closer in the two-hill condition than in the two-flat condition happens to be consistent with the data previously collected on participants' predicted effects (Tenhundfeld & Witt, 2017). When asked how a hill would influence perceived distance to a cone, the majority of participants (64%) indicated that the cone would look *closer* on the hill. This is indeed what the current participants tended to do. In other words, if participants altered their responses based on response bias, and the response bias is to estimate the hill cone as being closer, then they should move the comparison cone in the two-hills condition closer than the comparison cone in the two-flats condition. This pattern matches the present results.

This means that in the previous studies, if participants were using response bias to decide where to place the cone, then participants would have moved the cone on the hill closer than the cone on the flat plane. The action-specific perception response would be that participants place the cone on the hill farther than the cone on the flat plane. The results of the previous studies are consistent with the action-specific perception prediction, not the response bias prediction. The implications for interpreting the distance-on-hill effect is that it cannot be explained by response bias, and, if anything, response bias may even be working in the opposite direction and reducing the measure of the perceptual distance-on-hill effect.

It is important to point out that this experiment alone is not sufficient evidence of the distance-on-hill effect. Rather, the purpose of this experiment was to rule out response bias as a possible source of the effect. Several different strategies may have been used in this scenario for calculating distances. The important finding is that, unlike in the study with the apertures, the distance-on-hill effect did not fall into the El Greco fallacy.

General discussion

The current experiments give further evidence toward the claim that the distance-on-hill effect is truly perceptual. From a theoretical perspective, it is critical to distinguish whether action can influence perception directly, as opposed to alternative explanations such as response bias or judgment-based effects. However, the distinction between perceptual and nonperceptual effects is difficult to make empirically because there is no direct way to measure perception. Instead, behavioral responses are used to measure and infer a perceiver's experience. Differences in behavioral responses can be due to several factors other than perception. Therefore, it is critical to systematically examine these nonperceptual factors that could account for differences in the behavioral responses before concluding that the effect is perceptual.

Although there are no specific criteria for determining whether an effect is truly perceptual, a recent framework provides one way to evaluate the purported perceptual nature of an effect. According to this framework, there are six pitfalls that can account for an effect, which should be ruled out before making a perceptual claim (Firestone & Scholl, 2016). These pitfalls are (1) results being overly confirmatory; (2) effects being due to an influence on judgement, not perception; (3) effects due to response biases or experimenter demands; (4) effects being otherwise explainable by low-level differences in visual information; (5) effects due to attention; and (6) effects being due to memory instead of perception.

Firestone and Scholl (2016) claimed that a person's ability to act does not influence perception and that various demonstrations of purported action-specific effects are due to one or more of these pitfalls instead. For example, they found that the effect of holding a rod on estimated width of a doorway (Stefanucci & Geuss, 2009) could be explained by response bias (Firestone & Scholl, 2016). In another example, the effect of dart throwing performance on estimated target size (Wesp, Cichello, Gracia, & Davis, 2004) could be eliminated with a cover story, suggesting that the original effects could be explained by judgment-based processes (Wesp & Gasper, 2012).

It is important to note the asymmetry in the amount and type of evidence required to make claims for versus against a perceptual account. If a given effect is felled by a single pitfall, that is sufficient to provide evidence against a perceptual account for that particular task. To make a case for a perceptual account, evidence is needed to systematically rule out all six pitfalls. Thus, the necessary work to validate a claim of a perceptual effect is extensive because all of the potential pitfalls must be explored and eliminated as possible explanations.

That an action-specific effect can be perceptual has already been demonstrated with the Pong effect (for reviews, see Witt, 2017; Witt, Sugovic, Tenhundfeld, & King, 2016). The Pong effect is a phenomenon for which participants playing a

computer game, similar to the early video game Pong, rate the ball's speed as faster when the paddle is smaller, and thus less effective at blocking the ball, than when the paddle is bigger and more effective. A large body of research has evaluated the Pong effect across all six pitfalls and the evidence favors a perceptual explanation. This literature has been reviewed elsewhere (Witt, 2017) and thus will not be repeated here. That the Pong effect is perceptual does not necessitate, however, that all previously reported action-specific effects are perceptual. Each effect must be put through the wringer, so to speak, and evaluated against all pitfalls. The current work is an important step in providing this critical evaluation of the action-specific effect of perceived distance to targets on hills.

Pitfalls addressed by the present research

An overly confirmatory research strategy Firestone and Scholl (2016) argued that for a theory to be sound, there must be situations for which the theory predicts significant effects and also situations for which the theory predicts null results. They criticized action-specific accounts of perception for showing primarily confirmatory findings without as much emphasis on scenarios for which no effects are theorized to be found. Following up on their suggestion, the present study employed a situation for which null effects were correctly predicted by a perceptual account of the distance-on-hill effect.

In Experiment 5, participants completed a visual matching task on identical terrains. When the target and comparison cones were both presented on hills, the prediction according to a perceptual explanation is that participants would perceive the distance as farther in both cases, then they otherwise would if it were presented on the flat ground. The net result would be that any effect of the hill on perceived distance to one cone would be matched by a similar effect to the perceived distance to the other cone. Similarly, when both cones were presented on the flat ground, they should also be matched to be the same. No overall difference would be found in the distance matched between the cones, thereby producing a null effect.

Consistent with the perceptual account, there was a null effect of terrain when the terrains were both hills versus when the terrains were both flat. This is the result that would be expected if participants perceived the cones on the hill to be farther away for both the target cone and the comparison cone.

In both the hills condition and the flats condition, participants positioned the comparison cone closer than the actual target distance. This reflects a bias in the response itself, rather than in perception. Visual matching tasks often reveal biases. For example, one such bias arises from the starting location of the comparison cone, with closer estimates when the starting location is near than when the starting location is far. It is

critical when using these kinds of measures to counterbalance across conditions. For example, it would be poor design to have the comparison cone always start close for one condition and always start far for the other condition. However, as long as the design is counterbalanced such that there are equal trials in both conditions, these biases are effectively removed from the final outcomes. Thus, the conclusion from Experiment 5 speaks directly to Pitfall #1, which is that the perceptual account of action-specific effects can accurately predict a null effect. By demonstrating a predicted null effect, the body of research on the distance-on-hill effect is not entirely confirmatory.

Note that had the response been to move the comparison cone farther away when both terrains were hills compared with when both terrains were flat, this would have been compelling evidence against the action-specific account (as demonstrated previously with a different action-specific effect by Firestone & Scholl, 2014). That Experiment 5 ruled out this particular pitfall is an important step (though insufficient on its own) toward building a case for a perceptual explanation.

Perception versus judgement The second pitfall is that proposed action-specific effects do not reflect a change in perception, but rather a change in judgement. This would mean that when a participant estimated a distance as being farther, their estimated reflected a judgment-related process, such as the feeling that the distance felt farther or feeling that walking the distance would take more effort, rather than a genuine difference in perceived distance. For example, previous work showed that dart-throwing accuracy can influence judgments of target size (Wesp et al., 2004), but a follow-up study suggests these results were due to judgment-based processes rather than perception. Wesp and Gasper (2012) manipulated the original experiment by adding a cover story that told participants the darts are faulty, thereby explaining why performance might be low. With this cover story added, there was no longer a relationship between dart throwing performance and perceived size of the target. This suggested the results were due effects of judgement, not perception.

One common strategy in the literature for determining if an effect is perceptual is to examine evidence from a variety of measures (Philbeck & Loomis, 1997) across a variety of instructions (Woods, Philbeck, & Danoff, 2009). If the effect holds true across various measures with varying instructions, then it is consistent with the effect being perceptual. However, if the effect is only present when assessed with one type of measurement, then this suggests the effect is judgement based (Firestone & Scholl, 2016).

With respect to the distance-on-hill effect, a variety of measures have been explored, including blind walking, visual matching, and verbal estimates, that all show the same effect (Tenhundfeld & Witt, 2017). These converging measures show that the specifics of the task and instructions are not

the cause of the distance-on-hill effect. Future research could specifically manipulate instructions, such as telling participants to report on how far the target appears versus is (apparent vs. objective instructions, respectively) and also to tell them to take into account nonvisual factors and report how far away the target feels. If the effect emerges only with the latter instructions, this would be evidence for a judgment-based explanation rather than a genuine perceptual effect.

Demand and responses bias This pitfall reflects perhaps the most common criticism of action-specific effects on perception, the idea that it could be due to response bias or experimenter demands rather than to truly perceptual effects (e.g., Durgin et al., 2009). According to a response bias explanation, participants guess the hypothesis of the experiment and then act in a way that complies with how they think they should respond.

This pitfall was examined already with the distance-on-hill effect by interviewing participants as to whether they could guess the effect. Participants were given a scenario for which a person would be standing between two equidistant cones, one on a flat surface and one on a hill, and asked to predict if the person would see the cone on the hill as closer, farther, or the same distance as the one on the flat surface (Tenhundfeld & Witt, 2017). Only 30% of participants correctly identified the direction of the effect, while 63% of participants anticipated the opposite direction of the effect. Given that participants were unable to predict the effect and even more likely to predict the opposite effect, the distance-on-hill effect is unlikely due to response bias. Nevertheless, response bias can be tricky to completely eliminate as an explanation for results, so its potential role was further explored in Experiment 3.

Participants were given explicit feedback regarding their perceptual judgments. The addition of feedback was intended to create the expectation that the experimenter wanted the participant to answer as accurately as possible, rather than any expectation related to participants' potential inferences about the purpose of the study (such as distances are hypothesized to look farther on hills). This alleviates demands to respond differently to targets on hills versus the flat ground. Participants still showed the distance-on-hill effect even when the feedback would have minimized possible demand characteristics. This is evidence that is inconsistent with the response bias account and consistent the perceptual account. Additionally, Experiment 3 relates to the previous pitfall on judgement. Feedback to be accurate could have made participants focus on the distance of the cone, rather than how close the cone felt or how difficult it would feel to walk to the cone. That the distance-on-hill effect emerged even with feedback suggests that the cone looked farther when it was on a hill, rather than being judged as farther.

Memory and recognition The final pitfall is that the reported effects in accounts of action-specific effects on perception are not due to changes in perception, but rather to changes in memory. Because many tasks ask participants to make a judgement about size or distance after completing a task, there is a possible risk that such effects only affect the memory of the size or distance, but not the size or distance as it is being perceived. Many action-specific tasks include some delay between the visual stimuli and behavioral response, so a memory-based account is a distinct possibility. However, the distance-on-hill effect is still seen in a verbal estimation task, where there is no time gap between when the participant views the stimuli and makes a distance estimate (Stefanucci et al., 2005; Tenhundfeld & Witt, 2017). Given that the distance-on-hill effect is shown in various measures, some with the reference cone in view and others where the cone is not always in view, there is evidence that the task is not influenced by memory.

Limitations and next steps

While the current research addressed several of the pitfalls and made progress in ruling out various alternative explanations, there is still much work to be done before ruling the distance-on-hill effect as truly perceptual. There are two remaining pitfalls that still need to be ruled out (peripheral attentional effects and low-level visual differences) as well as other possible limitations of the present study.

The present study only used one angle for the hill across all five experiments. This can be seen as a possible limitation because the effects were only shown in one specific circumstance. Previous research has found the distance-on-hill effect to be shown with hills at various angles in both virtual reality and real life (Stefanucci et al., 2005). However, the effects were not present when the hill was at extremely low angles, such as 3 degrees and 6 degrees. This was hypothesized to be because the energetic differences would not be as apparent at those angles (Stefanucci et al., 2005). Future research needs to determine if the tasks in the present experiment replicate with hills of other angles as well as if the distance-on-hill effect remains constant across different angles or changes based on steepness.

Another critique of the action-specific account of perception is that the results are due to peripheral attentional effects, such as what the participant is looking at and for how long. As people perceive what they pay attention to, increased attention on one stimuli over another could influence perception as well (Firestone & Scholl, 2016). In the present study, we did not explicitly control the focus of duration of what participants viewed, as they were given freedom to look around the virtual world for as long as they pleased and in whatever way they found beneficial for the task. Therefore, it is a valid concern with the distance-on-hill effect with the current task.

Previous research has ruled out this pitfall for the Pong effect. When the task controlled where participants fixated during a Pong task, the Pong effect was still shown (Witt, Sugovic, & Dodd, 2016). While controlling for attention did not influence the Pong effect (and thus is unlikely to be a factor), attention could still be a possible explanation for other effects. Indeed, looking behavior moderated an effect of flying accuracy on estimated runway width, suggesting a role for attention in that task (Gray, Navia, & Allsop, 2014). Therefore, the distance-on-hill task needs to find a way to accurately measure or control for visual attention.

Further research could test the role of attention in the distance-on-hill effect in the same way the Pong effect was tested by creating a centralized fixation point on the screen. Another possibility includes controlling participants' looking time while completing the visual matching task or to measure time as another variable using time per trial. Another possibility includes using eye-tracking technologies to measure how long participants are looking where. Differential looking times could be indicative of differential strategies being used to estimate the distances.

Another proposed pitfall is that the results seen are due to low-level differences in the visual information, rather than being due to differences in perception. Because the studies manipulated the visual stimuli, visual differences could be causing these effects. Necessarily, there are clear low-level differences between the hill and flat conditions, so this pitfall is a valid concern for the distance-on-hill effect and one that will be difficult to resolve.

There are two proposed methods for mitigating the effects of low-level visual differences. The first way is to preserve the higher-level factors while eliminating the lower-level factors, which would include making sure the stimuli are made up of the exact same visual information, such as using the same lines that make up one stimulus to create another (Firestone & Scholl, 2016). A second suggestion is to do the opposite: preserve the low-level factors that could be causing differences, and eliminate the high-level factors, the differences that are actually hypothesized to show differences (Firestone & Scholl, 2014). One way to test this would be to create a scenario with the same exact visual stimuli but eliminate the component of action by having participants on a separate platform, sitting down, or anticipating another action that would not be manipulated by the distance-on-hill effect, such as throwing a ball to the targets. If there is still a difference between participants distance perception, that would mean that the effects could have been due to those low-level visual differences. If the distance-on-hill effect is truly perceptual, it should yield null results in that scenario. While these types of manipulations would be impossible to do with a real-life hill, they would be possible to do with the virtual environment used in this study.

Summary

These experiments have made important strides in determining whether the distance-on-hill effect is truly perceptual. Four of the six pitfalls have been addressed in the experiments, and the evidence is consistent with a perceptual explanation, and, in some cases, is inconsistent with a postperceptual explanation. To fully rule out all six pitfalls will take systematic exploration across several studies, as was done with the Pong effect (Witt, 2017). This exploration is necessary until either one pitfall clearly accounts for the distance-on-hill effect or none of them do. There is a certain level of asymmetry involved in determining such effects to be perceptual. All pitfalls must be systematically explored until either one pitfall can explain the result or all have been eliminated. This might seem like overkill, but action-specific effects challenge many theories of perception for which action is not considered a source of information for perception. Given the implications of action-specific effects for theories of vision, care must be taken to systematically explore each effect for alternative explanations.

Another advancement offered by the current experiments is the development of a reliable action-specific task that can be easily administered in virtual reality. The distance-on-hill effect, when measured using the visual matching task, revealed high intrasubject reliability. This makes it an effective tool for answering a variety of questions. Outstanding questions include the mechanism driving action's effect on spatial perception as well as whether there are individual differences in who shows these effects. Personal experiences have varied, with some researchers indicating that they and their students have never experienced these types of effects (Loomis, 2016), whereas many professional athletes report the exact experiences that would be predicted by an action-specific account of perception. If individual differences exist such that some people do not experience these effects while others do, then this could explain these discrepant reports. With the current task showing such high reliability, it is now ready to be used to answer these kinds of questions.

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