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Performance and ease influence perceived speed

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Abstract. According to the action-specific perception account, perception is a function of optical information and the perceiver's ability to perform the intended action. While most of the evidence for the action-specific perception account is on spatial perception, in the current experiments we examined similar effects in the perception of speed. Tennis players reproduced the time the ball traveled from the feeder machine to when they hit it. The players judged the ball to be moving faster on trials when they hit the ball out-of-bounds than on trials where they successfully hit the ball in-bounds. Follow-up experiments in the laboratory showed that participants judged virtual balls to be moving slower when they played with a bigger paddle in a modified version of Pong. These studies suggest that performance and task ease influence perceived speed.

1 Introduction

Athletes claim that, when they are playing well, the game seems to move in slow motion. Baseball player Ken Griffey Sr stated that when he is "in the zone, everything is in slow motion. I can slow the ball down and even stop it". Basketball player Bill Russell said "at that special level ... it was almost as if we were playing in slow motion". Tennis player John McEnroe said that when you are playing well "everything changes ... things slow down". Former No 1 tennis player Martina Navratilova also described being in the zone as an experience where the ball appears to travel in slow motion. Conversely, on a bad day the ball appears to fly by at seemingly impossible speeds. Are these anecdotes just an a-posteriori way to account for performance, or do they reflect an actual change in perception of speed? In the current studies we investigated this issue, and the data suggest that performance and ease to perform a task influence perceived speed.

Similar effects of performance are evident in spatial perception. For instance, softball players who are hitting better see the ball as bigger (Witt and Proffitt 2005). Golfers who are playing better see the hole as larger (Witt et al 2008). In laboratory-based tasks, when participants had to make an easy golf putt, the hole looked bigger than for participants who had to make a more difficult putt (Witt et al 2008). In other words, those faced with an easy task perceived the hole to be bigger than those faced with a difficult task. In another task where participants had to drop darts onto a target, the perceived size of the target negatively correlated with the number of attempts required to hit the target (Canal-Bruland et al 2010; Wesp et al 2004). Similar effects have also been found in children: the perceived size of the target correlated with the number of times they successfully hit the target with a ball (Cañal-Bruland and van der Kamp 2009).

Although much of the previous data is correlational, a new study on field goal kicking provides evidence for causation (Witt and Dorsch 2009). Participants estimated the size of an American Football field goal, and then completed ten attempts to kick a football through the field goal. After kicking, participants estimated the size of the field goal again. Post-kicking perceptual estimates correlated with kicking performance: participants who made more successful kicks perceived the goal to be bigger.

However, pre-kicking perceptual estimates did not correlate with subsequent performance. Participants did not initially see the goal as bigger (or smaller) and then kick better (or worse). Instead, the perceived size of the field goal was influenced by their kicking success after they attempted their kicks. This result suggests that performance influences perception.

These studies on performance and spatial perception provide support for the action-specific perception account (Witt, forthcoming). According to this account, optical information is scaled to the perceiver's ability to perform the intended action. As a consequence of this scaling, perceived dimensions of the environment look different depending on the perceiver's current performance. The action-specific perception approach challenges traditional views of perception that claim perception is an objective process that is independent of the perceiver's abilities and intentions. In contrast, evidence for the action-specific perception account reveals that, even when optical information is constant, aspects of the objects look different depending on the perceiver's ability to perform the intended action (for review, see Witt, forthcoming). Given the implications of these claims for theories of perception, it is important to understand the conditions under which action-specific perception effects occur.

The action-specific perception account makes a number of predictions as to the nature of the effects of performance on perception. First, the effect should be specific to the challenge posed by each object. If the object is a target that is difficult to strike, as in baseball, then the object should look bigger when the batter is hitting well. In contrast, if the object is a barrier that needs to be avoided, then, on a good day the object should look smaller. The potential finding that everything looks bigger to a perceiver who is playing well would challenge the action-specific perception approach. Second, the effects of performance should be apparent in all perceived dimensions of the environment that are relevant for action. Thus far, evidence has been documented in spatial perception, as reviewed above. In the current studies, we expand on the previous work by examining effects in perception of speed. If perceived speed is influenced by task ease and performance, then targets should look like they are moving slower when the task is easy or people are playing well, and targets should look like they are moving faster when the task is difficult or people are playing poorly.

2 Experiment 1: Perceived speed in tennis

In the first experiment, we examined perceived ball speed in tennis. Participants returned a tennis ball and then estimated its speed by reproducing the time the ball traveled from the feeder machine to when they hit it. If participants perceived the ball to be moving slower, they should indicate a longer travel time.

2.1 *Method*

2.1.1 *Participants.* Thirty-six students (thirteen females, twenty-three males) taking beginning ($n = 26$), intermediate ($n = 7$), and advanced ($n = 3$) tennis classes for course credit were recruited to participate.

2.1.2 *Stimuli and apparatus.* An automatic ball feeder was used to feed balls to participants. The settings were adjusted to feed balls at 80.5 or 128.7 km h^{-1} (50 or 80 miles h^{-1}) and at 15 or 40 topspin (forward rotation of the ball) depending on whether participants were returning the ball using a forehand or a backhand stroke, respectively. A laptop was positioned on a nearby bench (see figure 1). The laptop was used to estimate speed. Participants estimated speed by holding down the space bar, during which the static image of a tennis ball (approximately 8 cm in diameter) appeared. Two orange sports cones were used to estimate net height. Throughout the experiment participants were filmed with a camera set-up on the balcony to ensure an entire view of the court.

Figure 1. [In color online, see http://dx.doi.org/10.1068/p6699] Set-up for experiment 1. Participants returned balls that were fed from an automatic ball feeder, and then estimated the time the ball traveled from the machine to when they hit it by reproducing that duration on the laptop.

2.1.3 *Procedure.* Participants were run individually. On each trial, a ball was fed to the participant down the center service line from the automatic ball feeder. Participants stood behind the baseline at the center mark and attempted to return the ball by hitting it in play on the other side of the net. After each return, participants walked to the laptop to estimate the time that the ball traveled. To make this estimate, participants pressed and held the space bar for the same duration as they had perceived the ball to travel from the instant the ball left the machine to the instant when they hit it with their racket. As soon as they pressed the space bar, a picture of a tennis ball appeared and remained on the screen until they released the space bar. Participants estimated the duration of ball travel after every return. Each block contained 5 trials, and they completed 5 blocks (1 practice and 4 test blocks) with a different speed and topspin/stroke combination in each test block.

After completing all blocks, participants estimated the height of the net. They were given two cones and instructed to place the cones on the ground so that the distance between the cones matched the height of the net at the center of the court.

2.1.4 *Data analysis.* The speed of the ball roughly matched the designated speed on the feeder machine, but there was enough variation that actual travel times needed to be calculated for each trial. Actual ball travel times were calculated by using video footage of the experiment on Windows Movie Maker (30 frames s^{-1}). We calculated the actual travel time as the interval from the moment the ball was visible at the ball machine to the moment when the racket first struck the ball. Video data were not recorded for one participant, who was then excluded from analyses on duration estimates but included in the analysis for net height as we had all the data for that analysis.

2.2 *Results and discussion*

We calculated accuracy scores (actual duration divided by estimated duration) and compared trials in which participants successfully returned the ball with trials where their returns were unsuccessful. An accuracy score greater than 1 indicated that they perceived the ball to be moving faster and a score less than 1 indicated that they perceived the ball to be moving slower. According to our prediction, when the players are doing better, they should rate the ball as moving slower. Therefore, we took the mean speed accuracies for individual players when they hit the ball in-bounds (within the singles lines)

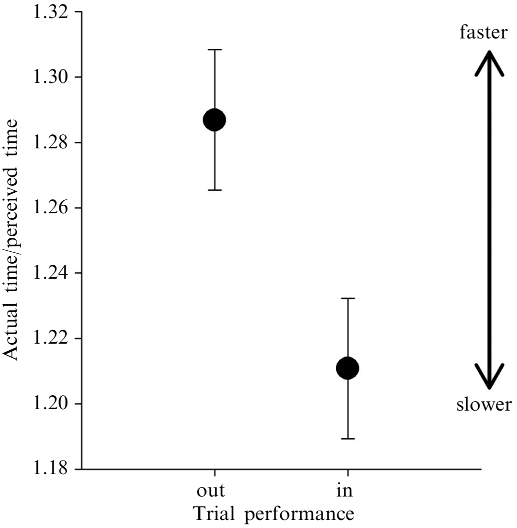


Figure 2. Accuracy in the time reproduction task as a function of whether participants successfully hit the ball in-bounds or out-of-bounds on each trial for experiment 1. The difference is approximately 8 km h^{-1} (5 miles h^{-1}). Error bars represent ±1 SE calculated within-subjects.

compared to when they hit the ball out-of-bounds. A paired-samples *t*-test revealed a significant effect for trial performance ($t_{34} = 1.77$, $p = 0.04$—always one-tailed given our specific predictions). Players judged the ball to be moving slower when they hit it in-bounds than when they hit it out-of-bounds (see figure 2). This difference corresponds to approximately 8 km h^{-1} (5 miles h^{-1}), so players judged the ball to be moving 8 km h^{-1} (5 miles h^{-1}) faster on trials in which they hit it out.

We also looked whether speed judgments were related to the type of error made upon ball return (see figure 3). Each shot was classified: the ball was hit in (In); out, because the ball was hit too early (Early); out, because the ball was hit too late (Late); or out because the ball was hit into the net or too deep but in line with the court (Net/Long). Balls that were hit to one side and too long were classified as Early or Late rather than as Net/Long. Not everyone committed each type of error, so we ran several paired-samples *t*-tests. None of the *t*-tests revealed significant effects (In versus Early: $t_{21} = -1.32$, $p = 0.10$; In versus Late: $t_{26} = -1.18$, $p = 0.12$; In versus Net/Long: $t_{34} = -1.39$, $p = 0.09$; Early versus Late: $t_{16} = 0.79$, $p = 0.22$).

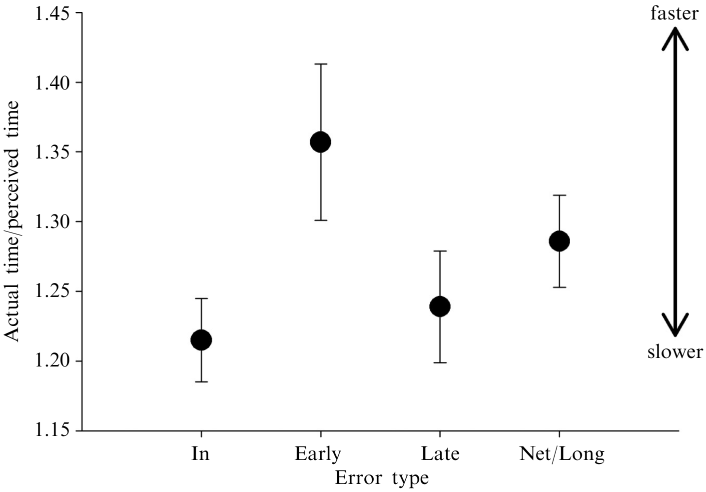


Figure 3. Accuracy in the time reproduction task as a function of type of performance error for experiment 1. Error bars represent ±1 SE calculated within-subjects.

An open question in the literature is whether perception is a function of expertise or of moment-to-moment performance. A study on golfers revealed a significant correlation with same-day performance but the correlation with handicap, a measure of overall skill, was not significant (Witt et al 2008). This result suggests that the perceptual effects might be more related to moment-to-moment performance. In the current data, the correlation between overall performance (percentage of balls successfully hit in-bounds) and speed judgment accuracy was not significant ($r_{34} = 0.01$). This also suggests that these effects are due to moment-to-moment performance rather than overall skill. However, our participants were not trained in estimating time intervals, so there was a large amount of between-subjects variability in perceived speed accuracy (minimum = 0.38, maximum = 4.98). Therefore, there may have been too much variance across subjects in our estimating task to reveal differences that could be related to overall performance, so we are hesitant to draw conclusions from this result.

Although we did not have equal numbers from the three tennis classes from which we recruited participants, we also looked at the data across groups. We found significant differences in performance (percentage of balls successfully returned) between participants in the three classes [$F_{2,34} = 7.23$, $p < 0.01$ (beginning: $M = 44.4\%$, SD = 0.14%; intermediate: $M = 58.2\%$, SD = 0.10%; advanced: $M = 70\%$, SD = 0.00%)]. There were also significant differences in the actual time that the ball traveled [$F_{2,34} = 3.46$, $p < 0.05$ (beginning: $M = 1.46$ s, SD = 0.12 s; intermediate: $M = 1.57$ s, SD = 0.04 s; advanced: $M = 1.56$ s, SD = 0.04 s)]. Thus, it is difficult to interpret the non-significant difference in estimated time [$F_{2,34} = 0.21$, $p > 0.81$ (beginning: $M = 1.41$ s, SD = 0.51 s; intermediate: $M = 1.28$ s, SD = 0.45 s; advanced: $M = 1.44$ s, SD = 0.06 s)]. However, when we looked at differences in accuracy (ratio of actual divided by estimated time), there were no differences across classes [$F_{2,34} = 0.88$, $p > 0.42$ (beginning: $M = 1.22$, SD = 0.44; intermediate: $M = 1.43$, SD = 0.45; advanced: $M = 1.10$, SD = 0.04)]. Given that we were more interested in moment-to-moment performance and thus did not recruit equally from different skill levels, it is difficult to interpret any differences, or lack thereof, across the groups.

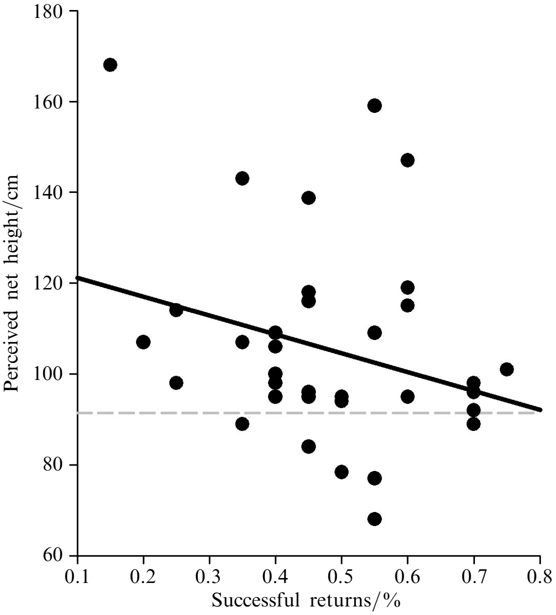


Figure 4. Perceived net height as a function of percentage of successful returns in experiment 1. The black solid line represents the linear regression of the data. The gray dotted line represents perfect accuracy. Each circle represents one or more participants.

We also looked at estimated net height as a function of percentage of balls successfully returned. Overall performance was significantly correlated with estimated net height ($r_{34} = -0.31$, $p < 0.05$—see figure 4). The less success a player had at returning the ball, the higher the net was judged. Similar to past results (eg Witt and Proffitt 2005), this result suggests a relationship between sports performance and spatial perception. However, this is the first result in which better performance led to a reduction in estimated size. While softball players who were playing better reported the ball as bigger, tennis players who were playing better judged the net to be lower. Thus, good performance does not always increase estimated size. Rather, the effects are specific to the goal of the task. In softball, the goal is to hit the ball, so players who are hitting better see it as bigger. In tennis, the goal is to hit the ball over the net, so players who are playing better see the net as lower.

3 Experiment 2: Perceived speed in Pong

The results from experiment 1 provide the first evidence to suggest that perceived speed is influenced by the player's ability to successfully return the ball. In order to corroborate this result, we ran a second experiment in which participants played a version of the classic computer game Pong. They controlled a paddle displayed on a projection screen with a joystick, and attempted to block a ball as it traveled across the screen. Then they estimated the speed of the ball. We varied the size of the paddle in order to manipulate ease to perform the task.

3.1 *Method*

3.1.1 *Participants.* Fourteen students (seven females, seven males) participated for course credit. (As a side-note, our participants were so young that few had ever heard of the game Pong!)

3.1.2 *Stimuli and apparatus.* Stimuli were presented on a projection screen. The projected area was 109 cm × 80.5 cm, and the background was black. Participants sat approximately 183 cm from the screen. A joystick was placed on the table directly in front of them. A white circle, which was 5 cm in diameter, served as the ball. A white rectangle, which served as the paddle, was only visible on test trials. The paddle was always 2 cm wide and positioned 9 cm from the right edge of the projection area. The height of the paddle was set to one of three heights (5.33, 16, or 32 cm).

3.1.3 *Procedure.* First, participants were exposed to the slow and fast speeds. Prior to each exposure, text on the screen said: "This is the slow speed" or "This is the fast speed". Then the ball traveled from left to right across the screen at 0.53 m s^{-1} (slow) or 1.86 m s^{-1} (fast). During training, the ball moved only horizontally with no vertical displacement. Each speed was shown three times, and all trials were randomized.

Then participants were tested to ensure that they could discriminate between the slow and fast speeds. On each trial, the ball appeared on the left and participants pressed a button on the joystick to begin the trial. The ball traveled across at either the slow or fast speed. Participants indicated whether the speed was slow or fast by pressing the left or right buttons on the joystick which were labeled with the words 'slow' and 'fast', respectively. Both speeds were presented five times, and trials were randomized for a total of 10 practice trials. They completed only 10 trials as the task was easy, and no one made any mistakes.

During the test trials, the ball moved across the screen and participants used the joystick to control a paddle to block the ball (similar to the computer game Pong). On each test trial, the ball appeared on the left side of the screen and the paddle appeared on the right. To begin the trial, participants clicked a button on the joystick and the ball traveled across the screen. The ball traveled at a constant speed ranging from 0.75 m s^{-1} to 1.94 m s^{-1}. The ball always moved along a diagonal. The horizontal movement was set to one of six speeds ranging from 0.53 m s^{-1} to 1.86 m s^{-1}, and the ball always moved from left to right. The initial vertical direction (up versus down) was randomized. The ball changed the vertical component of its direction whenever it reached the top or the bottom of the display. The ball also changed vertical direction at random, which made the task of blocking the ball more difficult. The ball was set to change vertical directions approximately 5% of the time.

Participants moved the joystick with their dominant hand to control the vertical placement of the paddle with the goal of stopping the ball. Participants were given visual feedback on their performance after each trial. If they successfully positioned the paddle to stop the ball, the ball stopped on the paddle and the paddle turned green. If they missed the ball, the ball continued beyond the edge of the display, and the paddle turned red. Then participants indicated if the speed of the ball was more like the slow speed or more like the fast speed by pressing the 'slow' or 'fast' button. This speed bisection task is modeled after typical time bisection tasks. Participants completed 10 blocks of trials. Each block contained 2 repetitions of each of 6 speeds with each of the three paddle sizes for a total of 36 trials per block. Speed and paddle size were randomized within each block.

3.2 *Results and discussion*

Participants judged the ball to be moving slower as the size of the paddle increased (see figure 5). We compared the point of subjective equality (PSE) across the three paddle conditions. PSEs were calculated from the slopes and intercepts generated by a binary logistic regression for each subject for each paddle condition. The PSEs were entered into a repeated-measures ANOVA, which revealed a significant effect of paddle length [$F_{2,26} = 9.85$, $p = 0.001$, $\acute{\eta}^2 = 0.43$ (small: $M = 1.24$ m s^{-1}, SD = 0.16 m s^{-1}; medium: $M = 1.01$ m s^{-1}, SD = 0.17 m s^{-1}; big: $M = 1.35$ m s^{-1}, SD = 0.17 m s^{-1}). A repeated-measures ANOVA with slopes for each paddle length as the dependent factor did not reveal a significant effect of paddle size ($F_{2,26} = 0.16$). This suggests that paddle size did not influence sensitivity to speed.

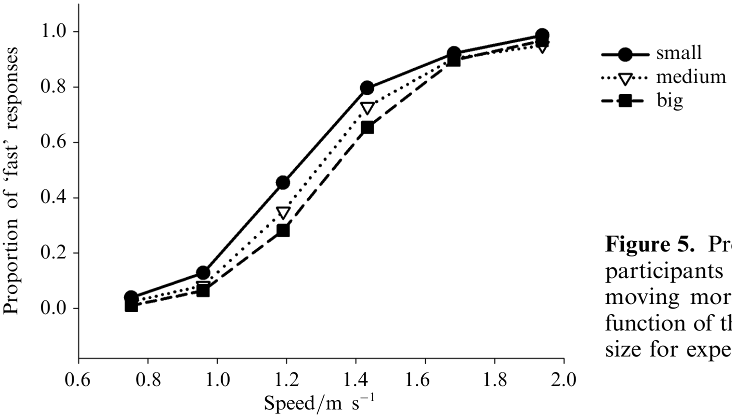
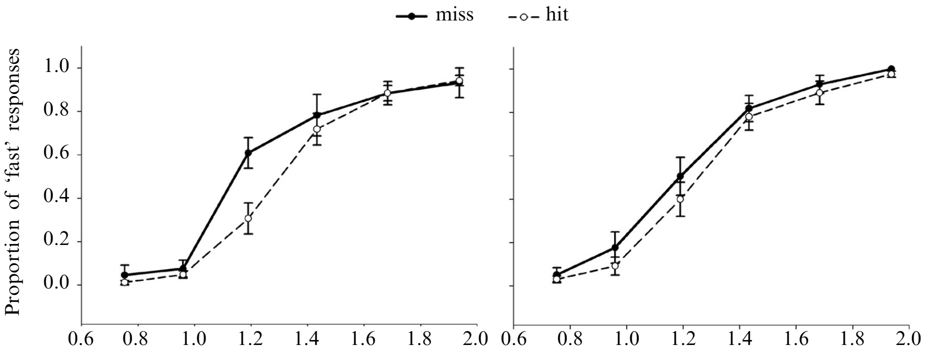


Figure 5. Proportion of trials in which participants judged the ball to be moving more like the fast speed as a function of the actual speed and paddle size for experiment 2.

Given that the ball was set to change directions at random, we also wanted to ensure that these effects were not due to differences in number of direction changes across the three paddle-size conditions. We entered the number of reversals as the dependent variable in a 3 (paddle size) × 6 (speed) repeated-measures ANOVA. The effect of paddle size was not significant [$F_{2,26} = 0.90$, $p > 0.41$ (small: $M = 1.70$ reversals, SE = 0.14; medium: $M = 1.48$ reversals, SE = 0.05; big: $M = 1.73$ reversals, SE = 0.18)].

This suggests that the differences in judgments of speed were not due to a difference in number of reversals. Not surprisingly, there was a significant effect of speed on number of reversals ($F_{5,65} = 39.40$, $p < 0.001$). There were more reversals for the slower speeds because there was more time for reversals to occur.

Performance, as assessed by the percentage of balls successfully stopped, differed across the three paddle sizes ($F_{2,26} = 275.39$, $p < 0.001$, $\acute{\eta}^2 = 0.96$). Participants were nearly perfect with the large paddle ($M = 98\%$, SD = 0.02%) and very good with the medium paddle ($M = 87\%$, SD = 0.04%), but were not as good with the small paddle ($M = 60\%$, SD = 0.10%). Given the relationship between paddle size and performance, we conducted separate 2 (hit or miss) × 6 (speed) repeated-measures ANOVAs for each paddle size with speed judgments as the dependent measure. There were not enough misses with the large paddle to conduct the analyses. With the medium paddle, there was a significant interaction between performance (hit versus miss) and speed ($F_{5,50} = 3.80$, $p < 0.01$, $\acute{\eta}^2 = 0.28$—see figure 6a). Participants judged the ball to be moving faster on trials in which they missed the ball but only for the intermediate speeds. With the small paddle, the effect of hit versus miss was not significant ($F_{1,13} = 1.95$, $p > 0.18$), nor was the interaction with speed ($F_{5,65} = 0.72$, $p > 0.61$—see figure 6b). It is not clear why individual trial performance influenced estimated speed for the medium but not the small paddle, though this might be related to the near-chance levels of performance with the small paddle. Participants were quite frustrated with the small paddle as the ball frequently changed direction just before it would have hit the paddle, resulting in a miss.



(a) (b)

Figure 6. Proportion of trials in which participants judged the ball to be moving more like the fast speed as a function of the actual speed and trial success for the (a) medium and (b) small paddle sizes in experiment 2.

4 Experiment 3: Pong replication

In the previous experiment, the training speeds matched the horizontal speeds at test, but not the overall speed when vertical displacement was taken into account. In order to ensure that effects from experiment 2 were not a result of training speeds being slower than test speeds, we re-ran the experiment with a training speed that was faster than the fastest speed at test.

4.1 *Method*

4.1.1 *Participants.* Twelve students (four females, eight males) who had not participated in the previous experiment participated for course credit.

4.1.2 *Stimuli, apparatus, and procedure.* Everything was the same as in experiment 2 except during fast trials at training where the ball moved at 2.13 m s^{-1}. During test trials, the speed varied from 0.75 m s^{-1} to 1.94 m s^{-1} as before.

4.2 *Results and discussion*

Participants judged the ball to be moving slower as the size of the paddle increased (see figure 7). PSEs and slopes were calculated as before. Paddle size significantly affected PSE [$F_{2,22} = 9.74$, $p = 0.001$, $\acute{\eta}^2 = 0.47$ (small: $M = 1.26$ m s^{-1}, SD = 0.14 m s^{-1}; medium: $M = 1.33$ m s^{-1}, SD = 0.10 m s^{-1}; big: $M = 1.36$ m s^{-1}, SD = 0.12 m s^{-1})]. There was no effect of paddle size on sensitivity, as assessed with slope ($F_{2,22} = 0.91$, $p > 0.41$). There were no differences in number of reversals across the three paddle conditions ($F_{2,22} = 0.14$, $p > 0.87$). As in the previous experiment, ease to perform the task influenced judgments of speed.

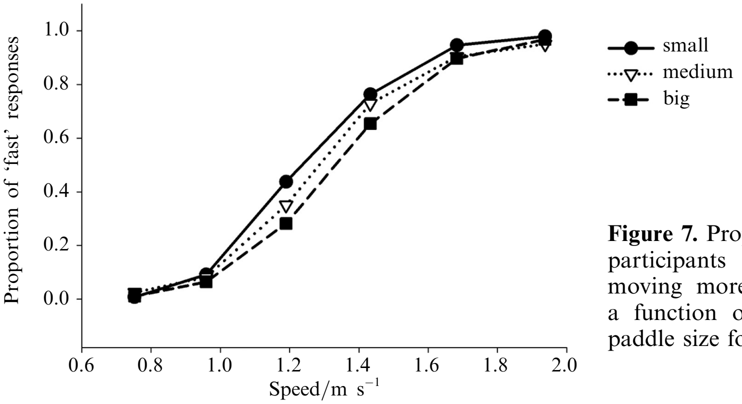


Figure 7. Proportion of trials in which participants judged the ball to be moving more like the fast speed as a function of the actual speed and paddle size for experiment 3.

5 Experiment 4: Hidden paddle

In experiments 2 and 3, players reported the ball to be moving slower when they played with the bigger paddle. We have interpreted these results as being due to the ease to perform the task. However, there were also optical differences across the three paddle conditions that could have influenced perceived speed independently of the participants' ability to block the ball. In order to differentiate whether these results are due to optical differences or differences in ease to perform the task, we conducted a final experiment where the only optical cues to specify the paddle were two thin horizontal black lines that were positioned at different extents from each other (see figure 8). These extents corresponded to the big, medium, and small paddle.

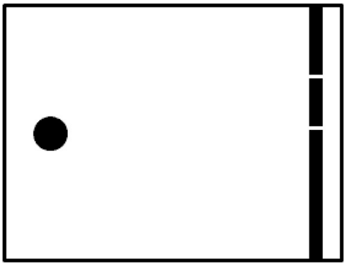


Figure 8. The visual display for experiment 4 with the black and white portions reversed. The paddle was placed on top of a white strip, so the only visual indication of the paddle was its outline, which consisted of two thin, black, horizontal lines.

5.1 *Method*

5.1.1 *Participants.* Eight students (six females, two males) who had not participated in the previous experiments participated for course credit.

5.1.2 *Stimuli, apparatus, and procedure.* Everything was the same as in experiment 3 except for the following changes. The paddle was placed on top of a white bar that covered the entire height of the display (see figure 8). Thus, the only optical information indicating the paddle size was the outline at the top and bottom of the paddle.

In contrast to previous experiments, the paddle did not change color depending on whether the participant was successful or not. Instead, the paddle remained white. Also, participants completed only 6 trials during training instead of 10.

5.2 *Results and discussion*

Participants judged the ball to be moving slower as the size of the paddle increased (see figure 9). After we calculated slopes and PSEs for each subject, it became clear that the data for one participant differed from the others. For the fastest speed, this participant reported the ball was moving more like the slow speed approximately 75% of the time when playing with the big paddle, so we removed her data and calculated PSEs and slope as before.

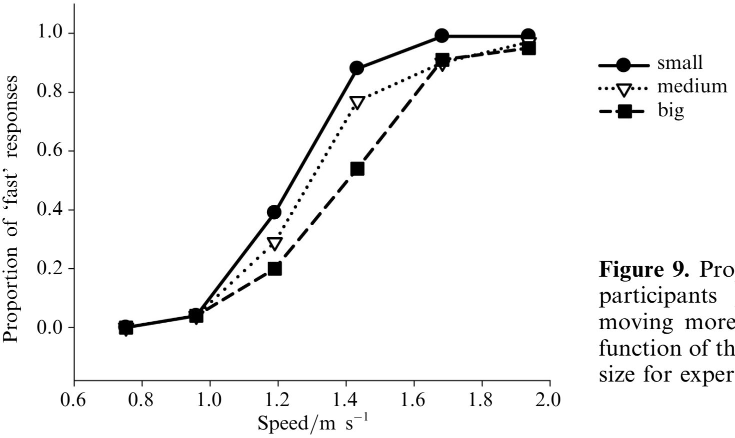


Figure 9. Proportion of trials in which participants judged the ball to be moving more like the fast speed as a function of the actual speed and paddle size for experiment 4.

Paddle size significantly affected PSEs [$F_{2,12} = 7.72$, $p < 0.01$, $\acute{\eta}^2 = 0.56$ (small: $M = 1.24$ m s^{-1}, SD $= 0.07$ m s^{-1}; medium: $M = 1.33$ m s^{-1}, SD $= 0.08$ m s^{-1}; big: $M = 1.40$ m s^{-1}, SD $= 0.10$ m s^{-1})]. The effect of paddle size on slope was not significant ($F_{2,12} = 0.32$, $p > 0.73$). Paddle size did not influence sensitivity to speed, but it did influence perceived speed. There were no significant differences in number of reversals across the three paddle conditions ($F_{2,14} = 0.13$, $p > 0.88$).

In this experiment, the paddle was hidden in the display, such that only the spacing between two thin horizontal lines specified the effective size of the paddle. Once participants started controlling the placement of the paddle, its size was apparent. However, some optical differences across the three paddle conditions were minimized, such as luminance contrast. Therefore, the result that the effective size of the paddle influenced judgments of speed is unlikely to be due to optical differences across the paddle conditions, as optical differences were minimized in this experiment.

6 General discussion

These studies reveal that performance and task ease influence judgments of speed. In tennis, balls that were successfully hit in-bounds were judged to be moving slower than balls that were hit out. In a modified version of Pong, the ball was judged to be moving slower when participants played with a larger paddle, which made the task easier. In addition, balls that were successfully stopped were judged to be moving slower than balls that were missed when participants played with the medium-sized paddle.

Consistent with the action-specific perception account (Witt, forthcoming), these results reveal a relationship between the perceiver's ability to act and perception of the surrounding environment. Furthermore, the studies also expand on the previous evidence in a number of ways, further strengthening the support for action-specific perception.

First, while previous studies showed that better performance was related to seeing the target as bigger (eg Witt and Proffitt 2005), in the current study we found that better tennis performance was related to seeing the net as lower or smaller. Thus, better performance does not lead to a general effect that everything looks bigger but rather to a more specific effect that is related to the task. According to the action-specific perception account, the relationship between perception and performance is a function of the goal of the task. For example, in softball, the ball is the target that should be hit, so better hitting results in perceiving it as larger. In tennis, the net is an obstacle to avoid, so better hitting results in perceiving it as lower. Thus, the current results provide support for the action-specific perception account by demonstrating a specific, rather than general, effect.

Second, the current studies expand on the previous evidence for the action-specific perception account by demonstrating an effect in perceived speed. The action-specific perception account predicts effects in perceived dimensions of the environment that are relevant for the action. Previous work has demonstrated effects in spatial perception. New evidence also suggests similar effects in perceived weight (Doerrfeld et al 2010). Participants rated a bag of potatoes as heavier if they intended to carry it alone than if they intended to carry it with another person. The current results reveal effects in perceived speed. Targets that were easier to block looked like they were moving slower. However, given that speed is the rate of change of an object's spatial location over time, the current results could be due to a change in perceived space such that the court looked smaller when the ball was hit out or the size of the Pong display looked smaller when playing with a smaller paddle. In this case, the current findings corroborate the previous results by providing an indirect measure of spatial perception.

We have described the effects as being based on both performance and ease to perform the task. However, performance and ease are closely related, and it is not clear that they lead to separate, independent effects. Most likely, ease influences anticipated performance, which influences perception. Thus, when participants played with the larger paddle, they could potentially anticipate having more success at blocking the ball, and thus perceived the ball as moving slower. Given that the action-specific perception account proposed effects based on anticipated actions (Witt, forthcoming), we believe that anticipated performance influences perception, and both previous performance and the ease to perform a task likely influence anticipated performance.

In these experiments, participants judged the speed of the ball after the ball had disappeared, and our measurements were based on a judgment. Therefore, despite describing these effects as perceptual, we cannot be sure if the effects of tennis performance or paddle size are perceptual or post-perceptual. Previous research on the effect of a frightening event on time perception revealed significant effects in subjective judgments of the time interval afterwards, but did not show significant effects on critical flicker fusion (Stetson et al 2007). The authors interpreted their results as evidence that a frightening event changes ratings of time intervals but does not actually slow down time in the mind. However, one needs to consider if slowing down time or seeing an object as bigger necessitates an increase in temporal or spatial resolution. An appropriate analogy is the difference between an optical and digital zoom. With both, an object can look bigger, but only the optical zoom will lead to increased sensitivity. Therefore, even if there is not a difference in sensitivity, as in the lack of effect with critical flicker fusion, this may not be evidence that the effect is not perceptual and only influences the judgments.

Another possibility is that paddle size influenced memory of speed and not perception of speed. Because speed was judged after the ball had stopped moving, it is impossible to disentangle these possibilities on the basis of our current data. Similar criticisms apply to studies on softball players and golfers (Witt and Proffitt 2005;

Witt et al 2008, respectively). However, follow-up studies demonstrated effects of performance on perception when looking at the targets themselves (Cañal-Bruland and van der Kamp 2009; Witt and Dorsch 2009; Witt et al 2008). In laboratory-based putting tasks, the effect of putting ease was just as big when viewing the hole while making a size judgment as when recalling the size of the hole from memory approximately 1 min later (Witt et al 2008). However, future research will need to determine if the paddle size influences perception or memory of speed.

Even if the effects are perceptual, one needs to consider if these findings can be explained by differences in the display that are independent of ease to perform the task. Optical differences that have been shown to affect perceived speed include contrast, surrounding motion, and size. Although we did not measure perception of these features, we can still relate our display to the previous research to examine if our effects are likely to be due to one of these visual differences as opposed to ease to perform the task.

With respect to contrast, previous research demonstrates that greater luminance contrast typically leads to increases in perceived speed (Anstis 2001; Blakemore and Snowden 1999). In experiment 4 we attempted to eliminate any luminance contrast differences across the three paddle conditions by making the elements in the display constant across the conditions. Therefore, we think it is unlikely that luminance contrast accounts for these effects.

With respect to surrounding motion, previous research reveals that perceived speed increases when the surround is stationary and decreases as the surround speed increases (Norman et al 1996). Although we did not record paddle movement, there likely would have been more movement in the position of the paddle with the smaller paddle. Therefore, according to a purely optical account, participants should have seen the ball as moving slower when playing with the smaller paddle that moved more. Instead, we found that participants judged the ball to be moving faster when playing with the smaller paddle.

With respect to size, the previous research reveals mixed results. When the spatial frequency of a grating is lower, which results in larger sections, perceived speed is slower (Chen et al 1998; Diener et al 1976). However, when a rotating cylinder is magnified, the perceived speed of rotation increases (Werkhoven and Koenderink 1993). Therefore, it is unclear whether a perceptually larger ball would have been perceived to be moving slower or faster. In this case, we must consider what would have led to perceiving the ball as appearing bigger or smaller. A visual size-contrast effect is possible with the bigger paddle leading to a perceptually smaller ball. However, we think this is unlikely, given that size-contrast effects are much weaker when the contrasting objects are dissimilarly shaped (Coren and Miller 1974; Rose and Bressan 2002).

Another possibility is that ease to perform the task influenced perceived size of the ball. Indeed, according to the action-specific perception account (Witt, forthcoming), targets that are easier to hit look bigger (Cañal-Bruland and van der Kamp 2009; Witt and Dorsch 2009; Witt and Proffitt 2005; Witt et al 2008). In this case, the results are consistent with an action-specific perception account, regardless of how perceived size relates to perceived speed. If a perceptually bigger ball looks to be moving slower, then perhaps our effects on speed are due to perceptual effects in perceived size instead. In this case, our results suggest that perceived speed provides an indirect measure of perceived size. This result is still consistent with the action-specific perception account. If a perceptually bigger ball looks to be moving faster, then our effects on perceived speed are reduced relative to what they would have been had ability not influenced perceived size. Thus, according to either interpretation, the current results support the action-specific perception approach.

In summary, we propose that ease to perform a task and performance on that task influence perceived speed. Tennis players judged the ball to be moving slower on trials in which they successfully hit the ball in-bounds than in trials where they were unsuccessful. Participants playing a modified version of Pong judged the ball to be moving slower when they played with a larger paddle that made blocking the ball easier. These results extend the action-specific perception account to demonstrate effects of action on the perception of speed.

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