

General and specific perceptual learning in radial speed discrimination

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The specificity of learning in speed discrimination was examined in three psychophysical experiments. In [Experiment 1](#), half of the observers trained with inward motion direction on a speed discrimination task, whereas the other half trained on the same task but with outward motion direction. The results indicated that significant training-based improvement transferred from a trained radial direction to an untrained radial direction. [Experiment 2](#) confirmed this transfer by showing that complete transfer was obtained even when stimuli moving in an untrained radial direction were used in the transfer task. In [Experiment 3](#), observers were trained at a viewing distance of 114 cm. The results showed that learning transferred partly to the viewing distances of 57 cm and 228 cm. In summary, the present transfer results indicate that reliable generalizations can be obtained in perceptual learning of radial speed discrimination.

Keywords: learning, motion-2D, detection/discrimination, perceptual learning, specificity, transfer

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Introduction

Perceptual learning refers to behavioral improvement in a perceptual task as a result of practice (Epstein, 1967; Fahle, 2005; Fahle & Poggio, 2002; Fine & Jacobs, 2002; Gibson, 1969; Gilbert, 1994; Sasaki, Nanez, & Watanabe, 2010). The majority of visual perceptual learning studies have found that the improvement was specific to the trained stimulus attributes, such as motion direction (Ball & Sekuler, 1982), orientation (Fiorentini & Berardi, 1980; Karni & Sagi, 1991; Ramachandran & Braddick, 1973), and retinal location (Shiu & Pashler, 1992). More recent studies, however, have found transferable learning when a task was made easier at the beginning of training (Ahissar & Hochstein, 1997; Liu, 1995, 1999; Rubin, Nakayama, & Shapley, 1997), when action video games were used for training (Green & Bavelier, 2003), when a small amount of easy training had been applied to a to-be-transferred motion direction (Liu & Weinshall, 2000), or when an irrelevant task had been trained at a to-be-transferred retinal location (Xiao et al., 2008).

In the present study, we investigated perceptual learning of speed discrimination in radial motion. In contrast to previous findings of learning specificity for motion direction (Ball & Sekuler, 1982), we found complete transfer of

improved speed sensitivity between trained (e.g., inward) and untrained (e.g., outward) motion directions. The transfer became partial, substantial nevertheless, only when the viewing distance was twice or half as long as the training viewing distance while the physical stimuli remained unchanged. These findings are surprising because it was not obvious from evidence in the literature that nearly complete transfer would occur in perceptual learning of speed discrimination.

In psychophysics, one perceptual learning study of speed discrimination used translational random dots. Saffell and Matthews (2003) found that learning of speed discrimination was highly task specific. Two motion stimuli in a discrimination trial differed in speed and, independently, in direction. Participants who were trained to discriminate speed could not transfer their learning to direction discrimination, and vice versa. In a separate study, Matthews and Qian (1999) found that speed discrimination of translational motion was direction invariant. However, they did not study learning of speed discrimination. So it remained unclear whether speed discrimination learning could transfer across motion directions. There was indirect evidence that such transfer may be unlikely. Sekuler (1992) suggested that speed discrimination in looming motion may be processed in the brain by unidirectional motion

units, because the discrimination threshold was comparable to that of translational (McKee, 1981) and rotational motions (Werkhoven & Koenderink, 1991). This finding suggests that speed discrimination in radial motion may be mediated by local, unidirectional motion units rather than units specific to radial motion.

In physiology, speed-tuned neurons at the middle temporal visual area (MT) have been found to play a direct role in translational speed discrimination (but not its learning). This is shown by the fact that neural activity was correlated with monkeys' behavioral responses on a trial-by-trials basis (Liu & Newsome, 2005). Moreover, the correlation was predictable from the speed tuning characteristics of an MT neuron. In addition, the behavioral threshold of the speed discrimination was lower than the neurometric threshold, suggesting a pooling process of neural signals for behavioral decisions involving speed discrimination. Although one potential candidate for carrying out this pooling process is at the medial superior temporal area (MST), where neurons selective to radial motion were found, the neural responses were little affected by stimulus speed (Duffy & Wurtz, 1991). The existing psychophysical and physiological evidence in speed discrimination generally suggests a role of local, unidirectional neurons at MT and possibly the primary visual cortex. Hence, due to motion direction selectivity of these neurons, it is reasonable to expect directional specificity of speed discrimination.

In the present study, we chose radial, rather than translational, motion stimuli primarily based on considerations of experimental design. Our participants were almost all inexperienced with psychophysical experiments, and involuntary eye movement was difficult to prevent with translational motion. Even if the stimulus duration is shortened to reduce the effect of eye movement (Ball & Sekuler, 1987), the so-called “covert eye movement” appears impossible to avoid (Georgopoulos, 1995). We therefore chose radial motion to reduce any systematic eye movements.

Experiment 1

Experiment 1 aimed to characterize the generalizability of speed discrimination learning. If speed learning is stimulus specific (as are most low-level visual tasks in perceptual learning), we would expect that the improvement in speed discrimination will not transfer from trained to untrained motion direction. At the other extreme, if speed learning is based on a general purpose mechanism, complete transfer may be observed.

Methods

Stimuli and task

As shown in [Figure 1](#), each trial consisted of two random dot stimuli with the same radial motion direction, either

inward or outward. Dots in the two stimuli moved with different speeds. Participants were instructed to fixate at the central red disk and were asked to report whether the first or second stimulus was faster. One second after the participant response, the next trial started. The stimuli consisted of 1000 black dots (0 cd/m^2 , 0.05° in diameter) that were uniformly distributed in a gray circular aperture (9.5° in diameter) at the stimulus onset. Each stimulus was presented for 400 ms with a central red fixation disk (11.71 cd/m^2 , 0.25° in diameter). When a dot moved out of the aperture, a new dot was generated. The luminance of the circular aperture decreased gradually from the center at 18.92 cd/m^2 to the edge at 0.5 cd/m^2 following a radial Gaussian function. Since this study was conducted in conjunction with a study on motion perceptual learning and motion aftereffect, we chose relatively slow speeds for the stimuli (Caset, Keeble, & Verstraten, 2002; Hiris & Blake, 1992; Williams & Sekuler, 1984).

Procedure

The experiment included three steps.

1. Pre-training psychometrics. The speed of the first stimulus was randomly chosen from one of the two speeds: $1.93^\circ/\text{s}$ and $2.17^\circ/\text{s}$, referred to as the basis speeds. If the speed of the first stimulus was $1.93^\circ/\text{s}$, the speed of the second stimulus was randomly chosen from the following five speeds: 1.45, 1.69, 1.93, 2.17, and $2.41^\circ/\text{s}$. If the speed of the first stimulus was $2.17^\circ/\text{s}$, the five speeds for the second stimulus were: 1.69, 1.93, 2.17, 2.41, and $2.65^\circ/\text{s}$. The ($1.93^\circ/\text{s}$, $1.93^\circ/\text{s}$) and ($2.17^\circ/\text{s}$, $2.17^\circ/\text{s}$) pairs were used in order to obtain more accurate fitting for the psychometric functions. In each session, 50 trials for each pairing condition were presented in a randomly interleaved manner. Trainees participated in two psychometric sessions, inward and outward motion, with the order counterbalanced between trainees. As a result, we measured four psychometric functions: (inward and outward motions) \times (the two basis speeds). It took about 60 min to complete these psychometric sessions. No feedback was provided. Before the measurement started, each trainee practiced with 20 trials.
2. Training on speed discrimination. The training used the two basis speeds: 1.93 and $2.17^\circ/\text{s}$. Each trainee practiced for 8 days with 600 daily trials. Each daily session lasted for about 45 min. Negative feedback was provided.
3. Repeat Step 1 to measure post-training psychometric functions.

Apparatus

The experiment used MatLab software (MathWorks) with the Psychophysics toolbox (Brainard, 1997; Pelli, 1997) and

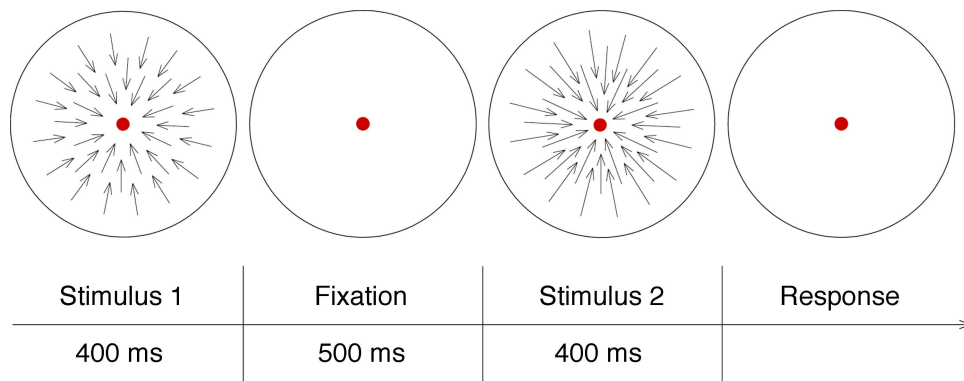


Figure 1. Schematic illustration of one trial with inward motion. The speed of the dots was constant within one stimulus but different from the speed of the other stimulus. The trainees decided which of the two stimuli was faster.

was run on a Celeron(R) 2.4-GHz personal computer in a dark room. The display was a 17" Sony G220 with a resolution of 1024 × 768 pixels and a vertical refresh rate of 75 Hz. The viewing distance was 114 cm.

Trainees

Fifteen students from the University of Science and Technology of China, Hefei, participated. Five students were trained with inward motion stimuli and five with outward motion stimuli. The remaining five were controls who were not trained during those 8 days but otherwise went through the same test procedure as the trainees. The participants were 20–25 years of age with normal or corrected-to-normal visual acuities. They were unaware of the purpose of the study and viewed the stimuli binocularly from a chin rest.

Results

Training

Figure 2 shows each trainee’s performance during the eight training days. Speed discrimination improved for all trainees, as indicated by the increased discrimination sensitivity index d' . When d' s were compared between the first and last days of training, this difference was statistically significant with $t(4) = 3.63, p = 0.022$ for the inward trainees and $t(4) = 3.80, p = 0.019$ for the outward trainees.

Transfer to the untrained radial motion direction

We used a cumulative Gaussian to fit each trainee’s psychometric function. Figures 3 and 4 show the proportion of responding “the second stimulus was faster” as a function of the relative speed difference (or the Weber

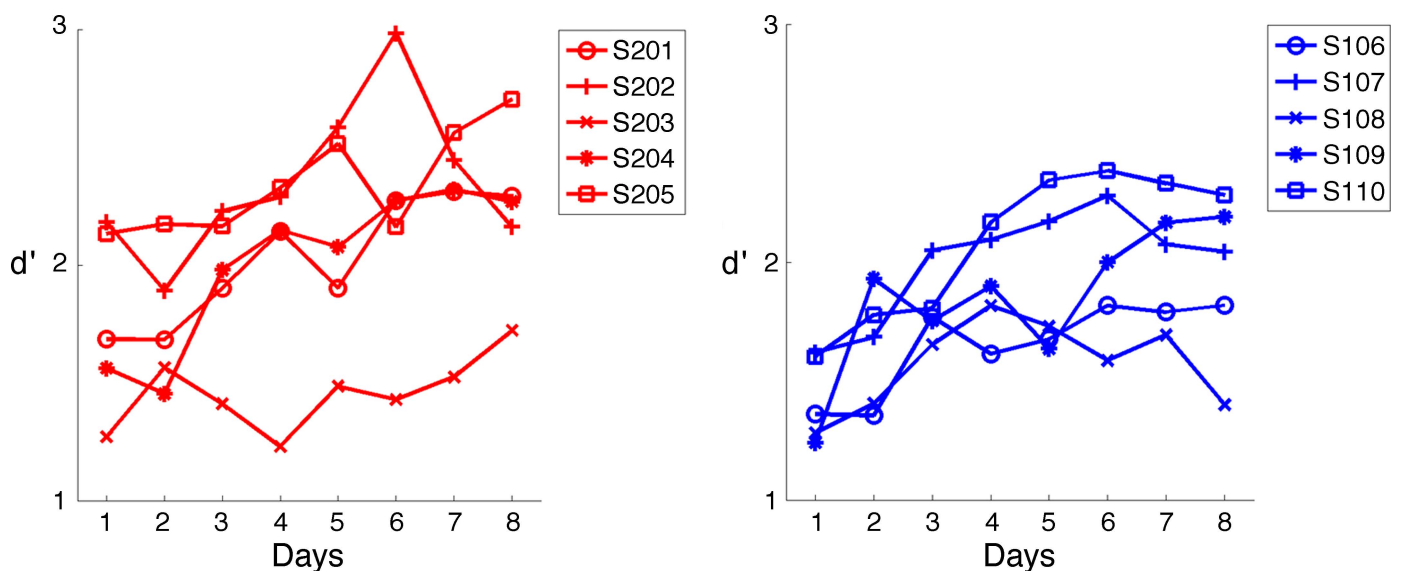


Figure 2. Discrimination index d' across 8 days of training. (Left) Inward motion training. (Right) Outward motion training.

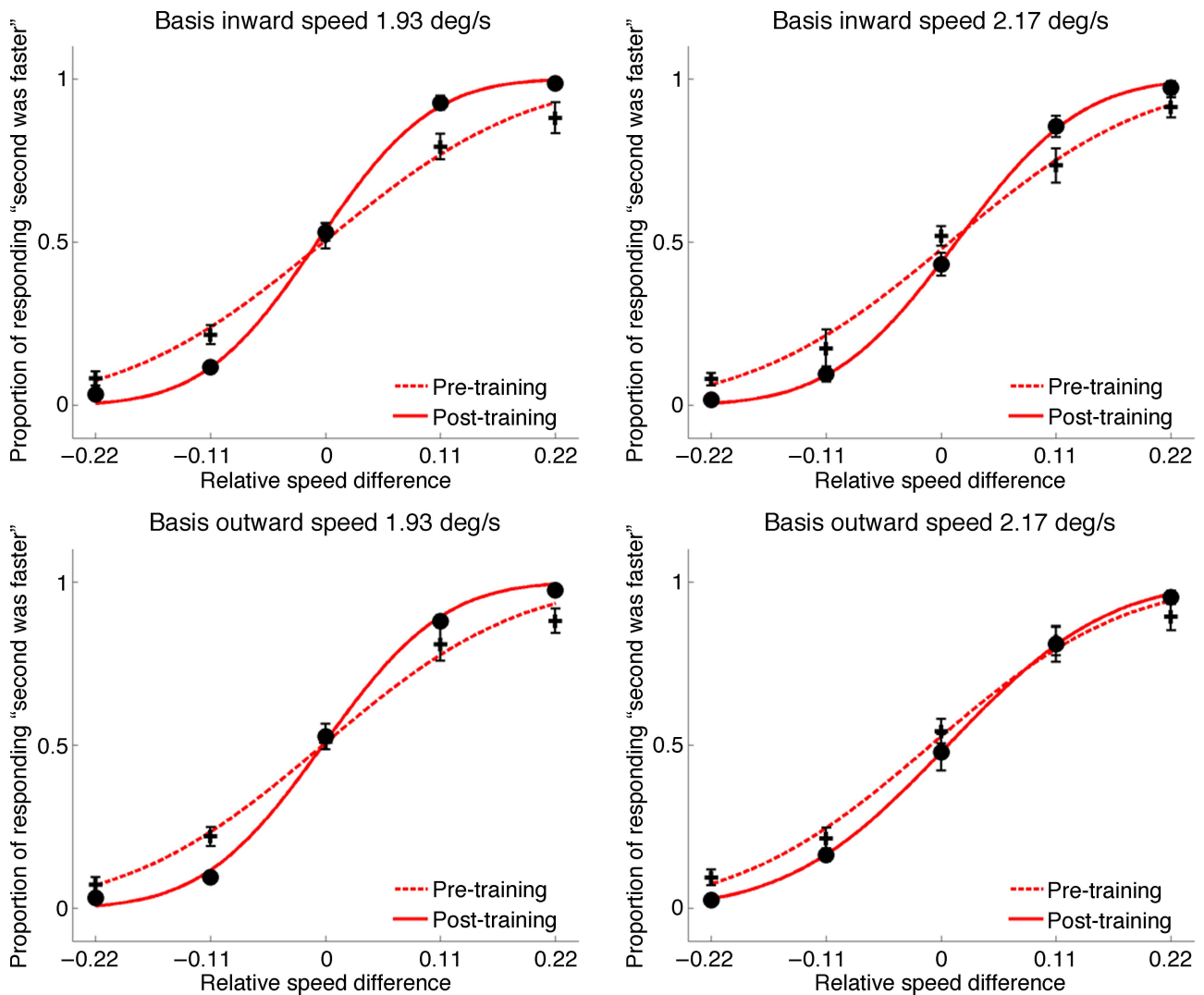


Figure 3. Psychometric functions for speed discrimination, averaged across the five inward motion trainees. (Top) Psychometric functions for inward motion. (Bottom) Psychometric functions for outward motion. (Left) When the basis speed was 1.93°/s. (Right) When the basis speed was 2.17°/s. Error bars here and below represent standard errors.

fraction). The mean of the Gaussian represents the bias (zero if the perceived basis speed was veridical), whereas the standard deviation (σ) represents the reciprocal of sensitivity (but different from d'). The goodness of fit, R^2 , was greater than 0.9 for all trainees' psychometric functions.

Figure 5 (left) shows the speed sensitivity ($1/\sigma$) of the 10 trainees at their trained and untrained radial motion directions for pre- and post-training psychometric functions.

A repeated measures ANOVA was conducted with one between-subjects factor (two training motion directions) and three within-subjects factors: basis speed (1.93 vs. 2.17°/s), psychometric motion direction (trained vs. untrained direction), and training (pre vs. post). No significant difference was found between the two training directions ($F(1, 8) < 1$) nor between the two basis speeds ($F(1, 8) < 1$). The main effect of pre- vs. post-training was significant ($F(1, 9) = 41.06$,

$p < 0.01$). Moreover, in psychometric measurements, the sensitivity in the trained direction was not significantly different from the untrained direction ($F(1, 9) < 1$). The interaction between training and the psychometric motion directions was not significant either ($F(1, 9) = 1.10$, $p = 0.32$). Therefore, these results indicate that learning completely transferred to the opposite, untrained radial motion direction.

The speed bias, measured by the mean of each fitted cumulative Gaussian function, did not change significantly after training ($F(1, 9) = 1.51$, $p = 0.25$). This finding indicates that speed learning mainly improved speed sensitivity but not decision bias.

At the individual level, we found significant within-subjects correlations between their d' improvements in training and their sensitivities increase in pre- vs. post-training psychometric measurements, both in the trained

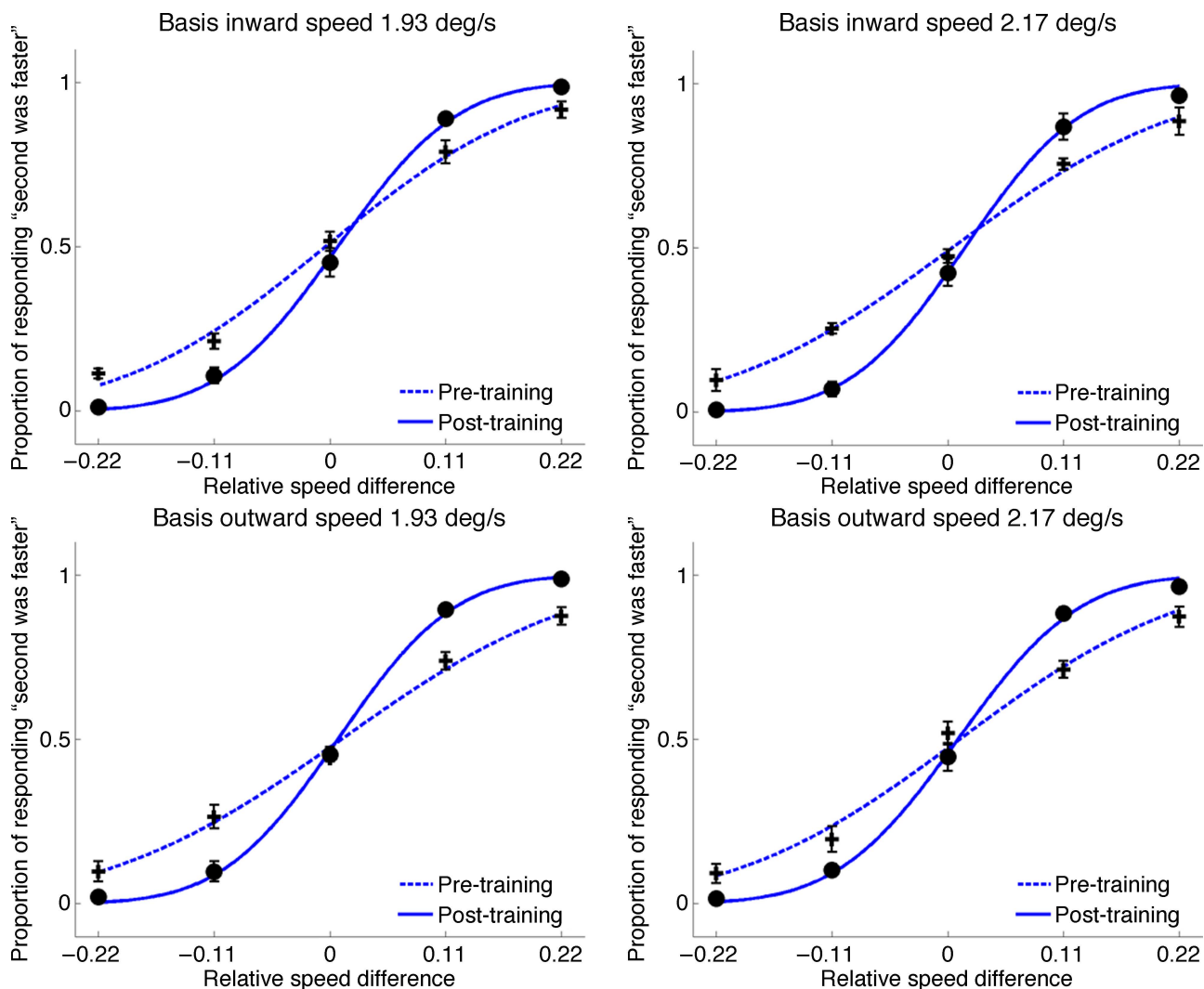


Figure 4. Same as Figure 3 except that the data are from the five outward motion trainees.

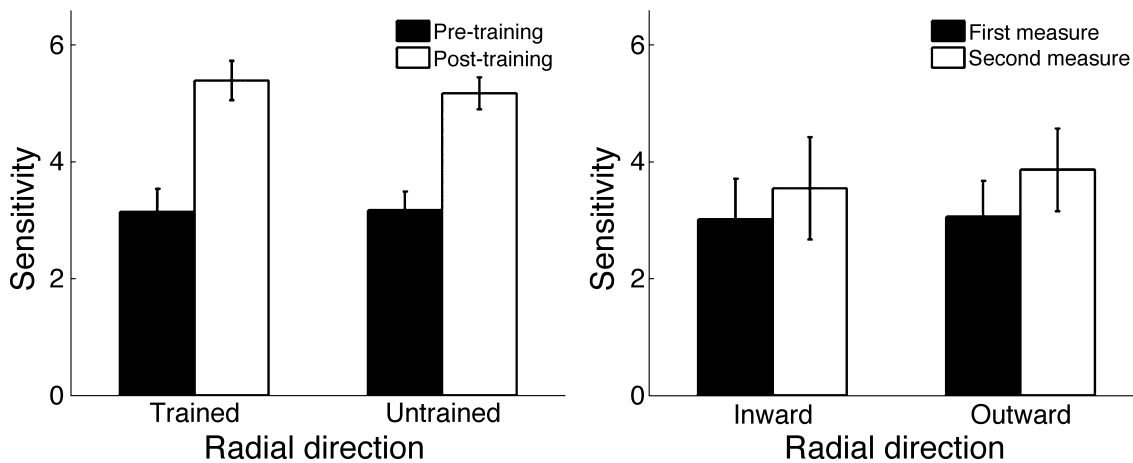


Figure 5. (Left) Speed sensitivities in trained and untrained radial directions for both inward and outward motion trainees. (Right) Data from five control participants who did not go through the training.

directions ($r = 0.83$, $p < 0.01$) and in the untrained directions ($r = 0.68$, $p = 0.03$).

For the control participants who were not trained during those 8 days, we found no significant change in either sensitivity ($F(1, 4) = 2.25$, $p = 0.21$) or bias ($F(1, 4) = 1.50$, $p = 0.29$). Figure 5 (right) shows speed sensitivities of the controls after collapsing data across the two basis speeds. When the controls were compared with the 10 experimental trainees, an ANOVA further revealed that the sensitivity difference was statistically significant ($F(1, 13) = 6.20$, $p = 0.03$). This interaction effect was due to training rather than observer differences, since there was no sensitivity difference between the two groups in the pre-training psychometric measurement ($F(1, 13) < 1$).

Experiment 2

Experiment 1 showed that the learning of speed discrimination completely transferred to the opposite radial motion direction, when the transfer was measured by using two stimuli of the same motion direction in a trial. The main purpose of Experiment 2 was to examine the robustness of the learning transfer using test stimuli that differed from the training stimuli. If the transfer observed in Experiment 1 was indeed complete, then similar results would be obtained even if the two stimuli in a test trial moved in opposite directions. We tested this possibility by conducting psychometric measurement using two stimuli with opposite radial motion directions in each trial.

The second purpose of Experiment 2 was to reduce the possibility that participants learned to track a dot's traveling distance and discriminate speeds accordingly. In Experiment 1, since each stimulus duration was constant and since the two stimuli in each trial moved in the same radial direction, it might be possible to track the traveling distance of a single dot to discriminate the speeds. However, this tracking would be difficult because tracking a dot's inward motion necessarily had to start off-fixation (which was against the explicit experimental instruction), and the starting position was always uncertain. For outward motion, because the dots were uniformly distributed at the stimulus onset within the display, there was only a small probability that a dot was present at the fixation at stimulus onset. Therefore, the putative tracking would be only effective when a dot at or near the fixation was tracked throughout the stimulus presentation time. By reversing the radial directions of the two stimuli in a trial, and by randomizing their order, we attempted to further minimize the effectiveness of this tracking strategy. Consequently, if the trainees learned to track during training when the two stimuli in a trial were always in the same radial direction, then this strategy would unlikely yield complete transfer in

the post-training psychometric measurement when the two stimuli moved in opposite directions. Finally, our third purpose conducting this experiment was to replicate Experiment 1 in a different laboratory.

Methods

Apparatus, stimuli, and task

Experiment 2 was conducted at the University of California Los Angeles (UCLA). The apparatus and stimuli were similar to those in Experiment 1, with the following differences. Participants viewed the stimuli through a dark tube that abutted the computer display. The stimuli were presented on a Dell Trinitron 19" monitor with 1600×1200 pixels. The monitor was calibrated with a Minolta CS-100 photometer. The diameter of the stimulus aperture was 9.6° of visual angle. The luminance of the circular aperture decreased from the center at 45.3 cd/m^2 to the edge at 2.18 cd/m^2 by following a radial Gaussian function. The luminance of the background was 0.16 cd/m^2 . The luminance of the dots was 0.16 cd/m^2 . Each dot subtended 0.024° (2×2 pixels).

The viewing distance remained 114 cm. The two basis speeds were different from those in Experiment 1, due to the monitor resolution difference between the two displays (since the viewing distance was the same). The basis speeds in Experiment 2 were 1.44 and $1.62^\circ/\text{s}$, and their motion was always inward during training, as shown in Figure 6. In the pre- and post-training psychometrics, each basis motion was paired with one of the following five outward motion speeds: 1.08 , 1.26 , 1.44 , 1.62 , and $1.80^\circ/\text{s}$ for basis $1.44^\circ/\text{s}$; 1.26 , 1.44 , 1.62 , 1.80 , and $1.98^\circ/\text{s}$ for basis $1.62^\circ/\text{s}$. In each trial, the order of the two stimuli was

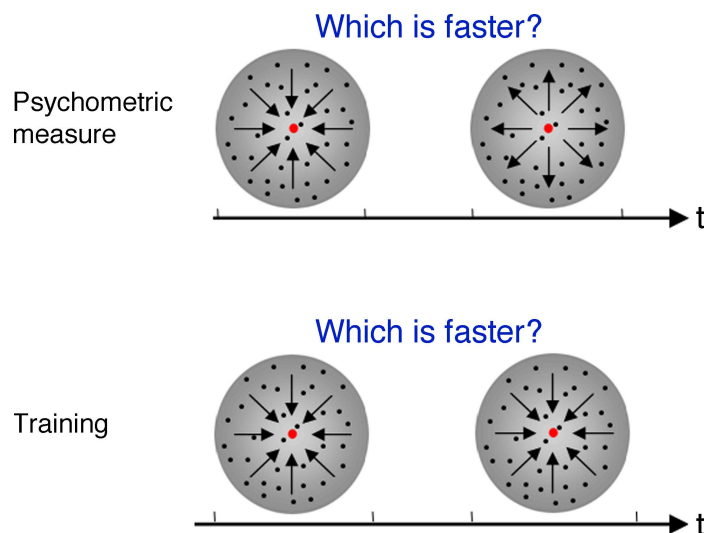


Figure 6. Illustration of stimuli used in Experiment 2. (Top) Stimuli for psychometric measurement moved in opposite directions. (Bottom) Stimuli in training always moved inward.

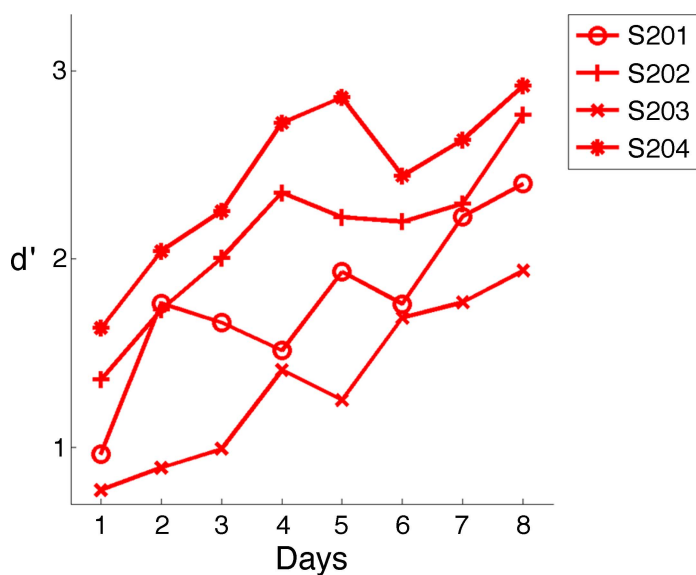


Figure 7. Discrimination index d' of the four trainees through 8 days of training in Experiment 2.

randomized. Participants decided whether the first or the second stimulus was faster.

Trainees

Four trainees with normal or corrected-to-normal visual acuities participated. One trainee was author ZL. The other three were naive to the purpose of the experiment.

Results

Learning

The four trainees improved their speed discrimination significantly after eight daily training sessions ($t(3) = 21.36$, $p < 0.01$; Figure 7).

Psychometric measurements

Figure 8 shows the average psychometric functions of the four trainees. For both basis speeds, the slopes of psychometric functions were significantly increased. Using a 2×2 repeated measures ANOVA (two basis speeds and pre- vs. post-training), we found no significant interaction ($F(1, 3) < 1$), but there was a significant main effect of training ($F(1, 3) = 51.40$, $p = 0.006$). These results suggest that training increased speed discrimination sensitivity, and learning transferred completely to the untrained, outward direction.

Similarly to Experiment 1, there was no significant bias difference between pre- vs. post-training ($F(1, 3) = 2.78$, $p = 0.19$). This result indicates that training had little impact on decision bias, but played an essential role in increasing sensitivity of speed discrimination.

Experiment 3

The purpose of Experiment 3 was to investigate the extent to which speed discrimination learning was specific to the perceived basis speeds used in training. In this experiment, participants trained with the viewing distance of 114 cm and were tested with 57, 114, and 228 cm viewing distances, while the physical stimuli were unchanged. The relative speed difference, or the Weber fraction, remained unchanged. We acknowledge that, because the physical stimuli were unchanged, the luminance and size of the stimulus co-varied with the viewing distance.

Methods

The stimuli and tasks were the same as in Experiment 1, except for the following details. Psychometric functions of

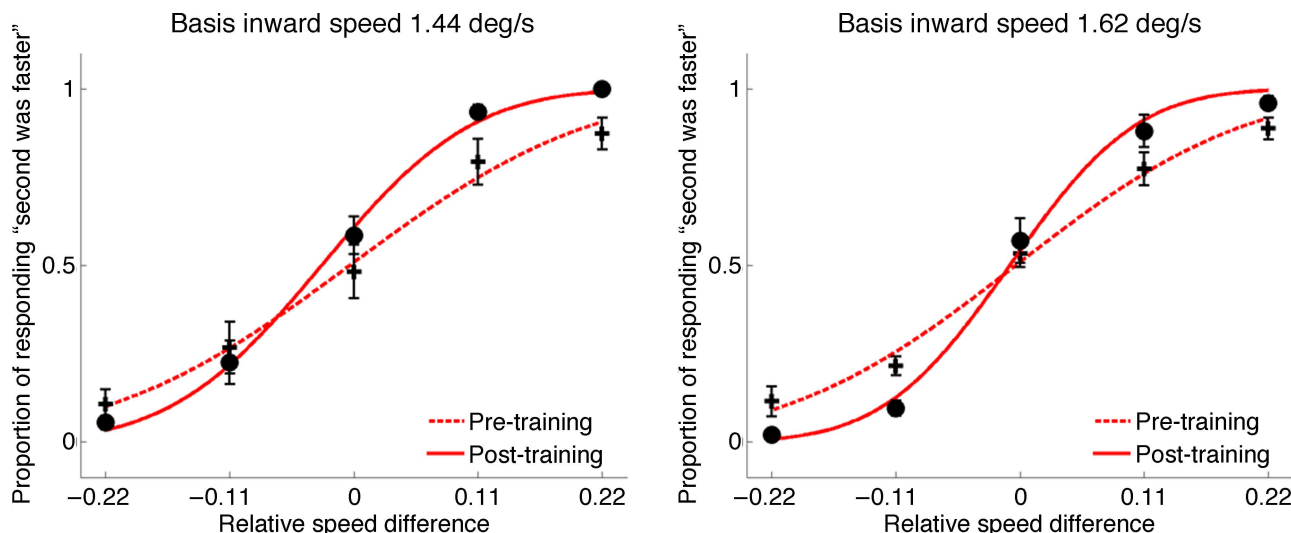


Figure 8. Average psychometric functions when the basis speed was (left) 1.44°/s and (right) 1.62°/s.

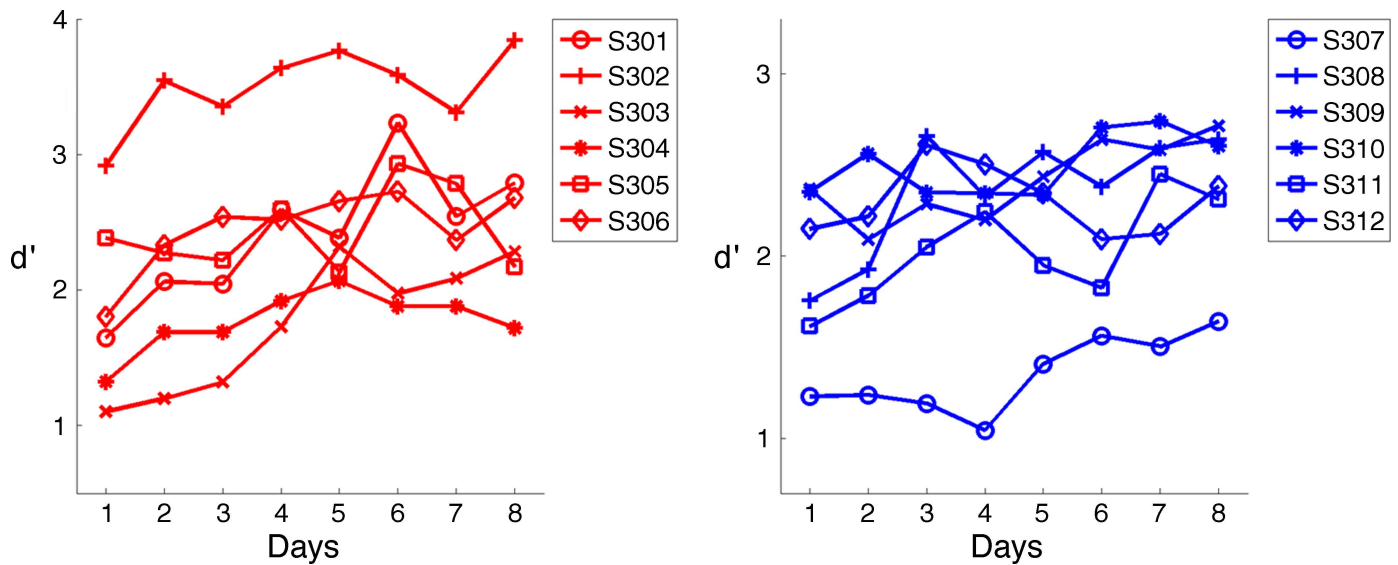


Figure 9. Discrimination index d' of each trainee throughout training at viewing distance of 114 cm. (Left) Inward training. (Right) Outward training.

inward speed discrimination were measured at 57-, 114-, and 228-cm viewing distances at both pre- and post-training for inward motion trainees. Similarly, outward psychometric functions were measured for outward motion trainees. The trainees practiced 20 trials before each psychometric measurement. The order of the psychometric measurements at the three viewing distances was counter-balanced across trainees.

Twelve fresh trainees were similarly recruited from the same population as in Experiment 1. Six were randomly assigned as inward trainees and six as outward trainees.

Results

Learning

Both the inward and outward trainees improved their performance as measured by their increased d' (Figure 9). The increased d' from the first to the last day was statistically significant: inward, $t(5) = 3.29$, $p = 0.02$; outward, $t(5) = 4.39$, $p < 0.01$.

Partial transfer to the untrained viewing distances

As shown in Figure 10, a cumulative Gaussian was again used to fit the psychometric function for each trainee at viewing distances of 57, 114, and 228 cm, respectively, and pre- and post-training, respectively. The goodness of fit, R^2 , was greater than 0.9 for all individual psychometric functions.

Figure 11 shows speed sensitivities for trained and untrained viewing distances. A repeated measures ANOVA was conducted on sensitivity with three within-subjects

factors (two basis speeds, three viewing distances, and pre- vs. post-training) and one between-subjects factor (motion direction: inward vs. outward). The main effect of viewing distance was significant ($F(2, 22) = 10.16$, $p < 0.01$), so were the main effect of pre- vs. post-training ($F(1, 11) = 115.80$, $p < 0.01$) and their interaction ($F(2, 22) = 4.33$, $p = 0.03$). The significant interaction indicates partial transfer of the learning from the trained to untrained viewing distances. The main effect of basis speed was not significant ($F(1, 10) = 2.99$, $p = 0.12$) nor was the main effect of motion direction ($F(1, 10) < 1$).

The slope of a psychometric function naturally depends on the unit chosen along the x -axis. Choosing the relative speed difference ($\Delta\text{speed}/\text{speed}$), as opposed to the absolute speed difference, makes the x -scale independent of the viewing distance. Indeed, the relative speed difference has been commonly used in plotting psychometric functions (De Bruyn & Orban, 1988; Liu & Newsome, 2005; McKee & Nakayama, 1984). Nevertheless, since the apparent partial transfer described above depended on the x -scale of the psychometric functions, we sought an alternative measure of performance that is independent of the x -scale, in order to strengthen the evidence for partial transfer.

To this end, we first calculated d' values at the relative speeds of $\pm 22\%$ and $\pm 11\%$ and then calculated the average d' per participant (d' at relative speed of 0% is undefined). A repeated measures ANOVA was conducted similarly as above. We found that performance changed significantly with training ($F(1, 10) = 100.53$, $p < 0.01$) and with viewing distance ($F(2, 20) = 12.35$, $p < 0.01$). The interaction between viewing distance and training approached significance ($F(2, 20) = 3.48$, $p = 0.051$). These results further confirmed partial transfer of improvement in terms

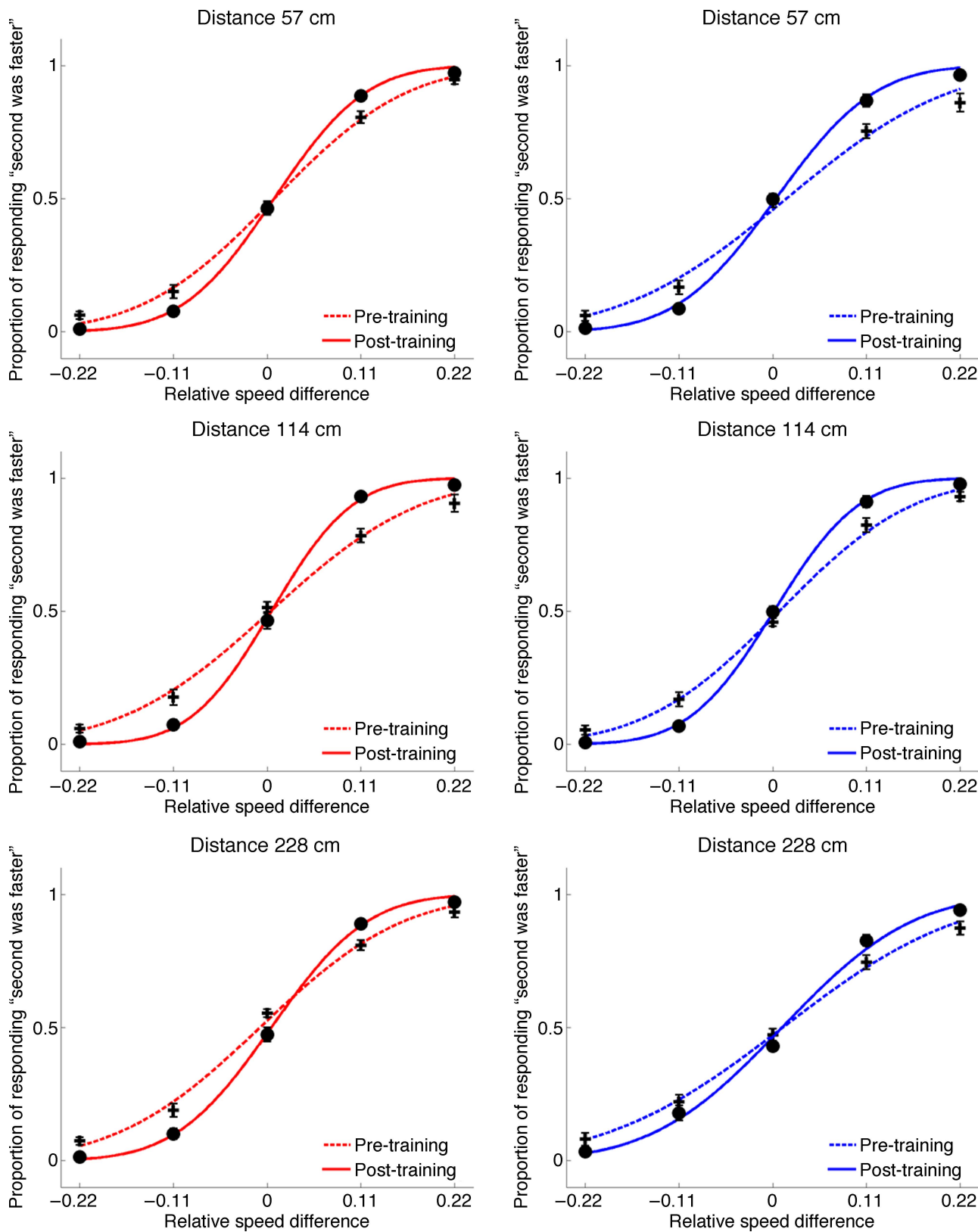


Figure 10. Average psychometric functions with three viewing distances in Experiment 3. (Left) Psychometric functions for inward motion trainees. (Right) Psychometric functions for outward motion trainees. Each row indicates different viewing distance: 114 cm was the trained distance; 57 and 228 cm were the untrained distances.

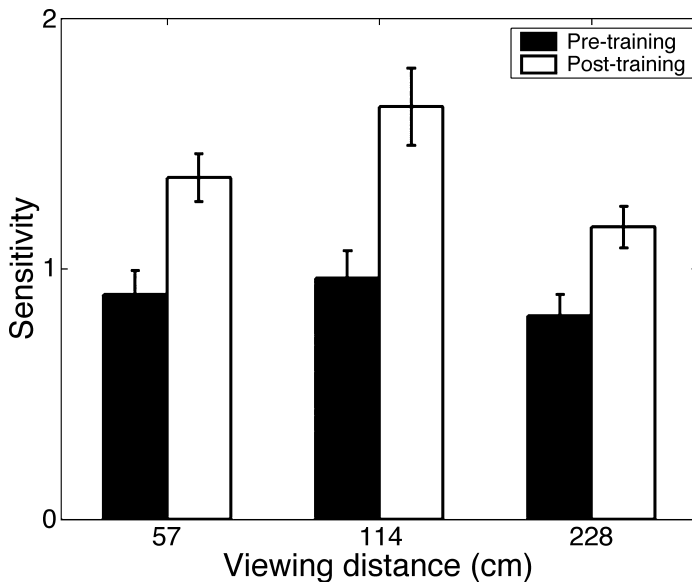


Figure 11. Speed sensitivity in trained and untrained viewing distances for both inward motion and outward motion trainees. The black bars indicate speed sensitivity pre-training; the white bars indicate speed sensitivity post-training.

of d' from the trained viewing distance to untrained distances. The main effect of motion direction in the training was not significant ($F(1,10) < 1$).

Discussion

In the present study, we found that learning in speed discrimination of radial motions transferred completely to the opposite motion directions. This learning also partially transferred when the viewing distance was doubled or halved, while the physical stimuli remained unchanged. In other words, the learning was partially specific to the trained absolute speed difference, in that when this difference was twice or half as long as the original, the improvement did not completely carry over.

Our results of transfer between opposite radial directions are consistent with the hypothesis that transfer of learning was enabled when task difficulty was reduced (Ahissar & Hochstein, 1997; Liu, 1995, 1999; Rubin et al., 1997). This is because all participants' discrimination index d' values on the first day of training were close to or above 1. Our results of partial specificity to viewing distance also indicate that generalization of learning in radial speed discrimination was conditional. Namely, complete transfer was possible for certain stimulus attributes (radial motion direction) but not for others (viewing distance). The transfer was impossible without training stimuli even if the temporal duration of training was retained (Experiment 1). These training specific results were consistent with the prior study in motion direction discrimination (Liu & Weinshall, 2000), when transfer was

impossible if there were no training stimuli or if the stimuli remained similar but the task was switched from direction discrimination to contrast discrimination. The results of partial specificity when the viewing distance was halved or doubled could not be due to any task difficulty change, because the Weber fraction of relative speed difference was the same when the viewing distance was changed.

It remains, therefore, an open question whether transfer will be affected if task difficulty in training is changed. Jeter, Doshier, Petrov, and Lu (2009) predicted that the degree of transfer would not depend on the difficulty of training task, but only on the difficulty of the transfer task, based on their study on orientation discrimination of gratings. This prediction amounts to a null effect that is difficult to confirm, particularly given large individual differences in motion perceptual learning. Nevertheless, this prediction is theoretically important and deserves direct verification in the future.

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