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J Neurophysiol 104:3305-3311, 2010. First published 14 July 2010; doi:10.1152/jn.00286.2010

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Learning to Discriminate Face Views

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Submitted 22 March 2010; accepted in final form 7 July 2010

Bi T, Chen N, Weng Q, He D, Fang F. Learning to discriminate face views. *J Neurophysiol* 104: 3305–3311, 2010. First published July 14, 2010; doi:10.1152/jn.00286.2010. Although perceptual learning of simple visual features has been studied extensively and intensively for many years, we still know little about the mechanisms of perceptual learning of complex object recognition. In a series of seven experiments, human perceptual learning in discrimination of in-depth orientation of face view was studied using psychophysical methods. We trained subjects to discriminate face orientations around a face view (i.e., 30°) over eight daily sessions, which resulted in a significant improvement in sensitivity to the face view orientation. This improved sensitivity was highly specific to the trained orientation and persisted up to 6 mo. Different from perceptual learning of simple visual features, this orientation-specific learning effect could completely transfer across changes in face size, visual field, and face identity. A complete transfer also occurred between two partial face images that were mutually exclusive but constituted a complete face. However, the transfer of the learning effect between upright and inverted faces and between a face and a paperclip object was very weak. These results shed light on the mechanisms of the perceptual learning of face view discrimination. They suggest that the visual system had learned how to compute face orientation from face configural information more accurately and that a large amount of plastic changes took place at a level of higher visual processing where size-, location-, and identity-invariant face views are represented.

INTRODUCTION

Perceptual learning is the phenomenon that training can improve sensory feature discrimination and object recognition (Fahle and Poggio 2002). It has been observed in all sensory modalities and has been studied intensively in past decades because of its close links to cortical plasticity (Fahle 2005; Gilbert et al. 2001). In vision, the majority of perceptual learning studies focus on experience-dependent changes taking place at early processing stages in the visual system. It has been shown that training can improve performance in discriminating many elementary visual features, including contrast (Yu et al. 2004), orientation (Schoups et al. 1995), spatial phase (Berardi and Fiorentini 1987), stereoacuity (Fendick and Westheimer 1983), hyperacuity (Fahle and Edelman 1993), motion direction (Ball and Sekuler 1987), and texture (Karni and Sagi 1991). One of the central questions in perceptual learning is its specificity and generalization (transfer), which have profound implications for the underlying neural mechanisms (Gilbert et al. 2001). Perceptual learning in low-level vision is usually characterized by its specificity to trained visual attributes like retinal position, orientation, or eye. These characteristics point to early visual cortical areas as its neural

substrate, where the visual topography is precisely mapped, the receptive fields are small, orientation tuning is sharp, and monocular neurons exist. Indeed, recent single-unit and brain imaging studies confirmed this idea and showed that the locus of cortical changes accompanying perceptual learning could be as early as in V1 (Furmanski et al. 2004; Pourtois et al. 2008; Schoups et al. 2001; Schwartz et al. 2002; but see also Ghose et al. 2002).

Perceptual learning also occurs with more complex visual stimuli such as shape, object, and face, as shown by several psychophysical studies. (Furmanski and Engel 2000; Gold et al. 1999; Sigman and Gilbert 2000). Parallel to low-level vision, the effect of object recognition training was also specific to the trained set of objects (Sigman and Gilbert 2000) but showed a higher degree of generalization than low-level vision (e.g., complete transfer across changes in object size; Furmanski and Engel 2000), which is in accordance with the size-invariant object representation in high-level visual cortex (Ito et al. 1995). Single-unit studies in monkeys have shown that training on recognition and discrimination of objects could induce changes in the strength and object selectivity of neuronal responses in the inferior temporal visual cortex (Baker et al. 2002; Freedman et al. 2006; Sigala and Logothetis 2002). Functional MRI (fMRI) studies in human subjects found that object recognition training could either enhance cortical responses in object-selective areas (Grill-Spector et al. 2000; Kourtzi et al. 2005; Tarr and Gauthier 2000) or change the spatial distribution of activity to trained objects in extrastriate cortex (Op de Beeck et al. 2006).

Although perceptual learning in high-level vision is receiving increased attention from researchers, relative to perceptual learning in low-level vision, its characteristics remain largely unknown and its neural mechanisms are still elusive. Here, we carried out seven experiments to systematically study the characteristics of perceptual learning in face view discrimination. *Experiment 1* established the basic learning protocol and showed that, after training, performance in face view discrimination could significantly improve in an orientation-specific and long-lasting manner. In *experiments 2–7*, we measured the transfer of the perceptual learning across changes in face size, face part, visual field, face identity, in-plane orientation, and object category. With the measurements of specificity and transfer, we can infer what is learned during training and the cortical locus and the neural mechanism of the face view learning (Fahle 2005).

We believe that face view learning is a good starting point to study perceptual learning in high-level vision. First, significant advance has been made in understanding how face view is represented in the visual cortex. In monkey, face view-selective neurons clustering in the superior temporal sulcus (STS) and inferior temporal cortex (IT) have been well studied (De

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Souza et al. 2005; Desimone et al. 1984; Perrett et al. 1985, 1991). Compared with neurons coding other complex visual stimuli, these neurons are better understood in terms of tuning function, receptive field properties, cortical circuitry, and functional architecture. In human, fMRI and transcranial magnetic stimulation studies found that face views are represented hierarchically in high-level visual cortex (Andrews and Ewbank 2004; Fang et al. 2007; Pitcher et al. 2007): occipital face area (OFA) represents face parts and fusiform face area (FFA) and STS represent face views with different angles. All these findings in monkey and human would help to build a close linkage between psychophysical measurements and neural activity. Second, unlike previous high-level visual perceptual learning studies using a visual search or object identification task, the orientation of face view can be manipulated in a continuous and quantitative way. Similar to low-level visual perceptual learning studies, just noticeable difference (JND) can be measured to quantify subjects' performance in face view discrimination, which makes the comparison between high- and low-level visual perceptual learning more straightforward.

METHODS

Subjects

A total of 50 naive subjects (23 male and 27 female) participated in the study. The numbers of subjects in *experiments 1–7* were 8, 8, 6, 8, 7, 6, and 7, respectively. None of them was involved in more than one experiment. They were right-handed with reported normal or corrected-to-normal vision and had no known neurological or visual disorders. To the best of our knowledge, no study has shown that hand laterality could affect face view discrimination performance. Their ages ranged from 19 to 23 yr. They gave written, informed consent in accordance

with the procedures and protocols approved by the human subjects review committee of Peking University.

Stimuli and designs

Three three-dimensional (3D) face models were generated by FaceGen Modeler 3.1 (<http://www.facegen.com/>). No hair was rendered. One face model was the default average face (Fig. 1A) in the software, and the value of texture gamma correction was set to 2. This model was used in most experiments except *experiment 5*. The other two models were rendered with two face images: Jim and Anti-Jim (Fig. 2D), which were a face/anti-face pair developed by the Max Planck Institute for Biological Cybernetics (Leopold et al. 2001). These two models were used in *experiment 5* and our previous study (Fang et al. 2007). An M-like paperclip model (Fig. 2F) was rendered with OpenGL for *experiment 7*. It was also used in a study by Fang and He (2005).

Visual stimuli were generated by projecting a 3D stimulus model with variant in-depth rotation angles onto the monitor plane with the front view (0°) as the initial position. Both left and right rotations were executed, with a step size of 0.2° . The stimuli (except those in *experiment 2*) extended $3 \times 3^\circ$ of visual angle. They were presented on an IYAMA HM204DT 22-in monitor, with a spatial resolution of $1,024 \times 768$ and a refresh rate of 100 Hz. Subjects viewed the stimuli from a distance of 60 cm. Their head position was stabilized using a chin rest and a headrest. Throughout the experiments, subjects were asked to fixate a small white dot presented at the center of the monitor.

Each subject underwent eight daily training sessions to discriminate face views around the face orientation of 30° , either left tilted (-30°) or right tilted ($+30^\circ$). A daily session (~ 1 h) consisted of 25 QUEST staircases of 40 trials (Watson and Pelli 1983). In a trial, 30 and $30 \pm \theta^\circ$ face side views were each presented for 200 ms and separated by a 600 ms blank interval (Fig. 1B). Their temporal order

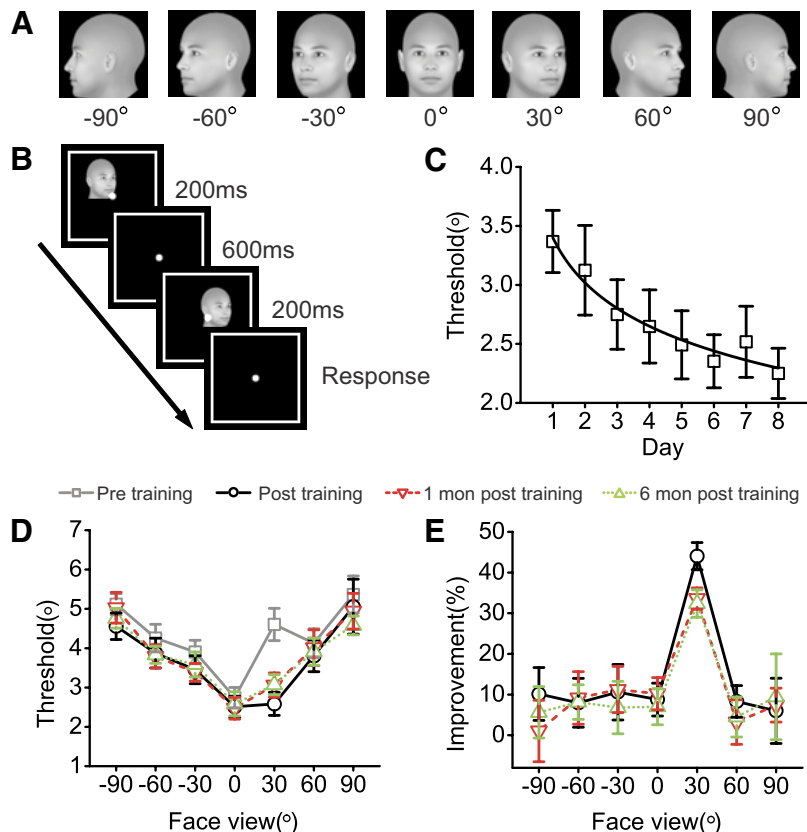


FIG. 1. Training on a face view resulted in improvement in face view discrimination at the trained orientation. *A*: face views at 7 orientations used as test stimuli. Subjects were trained at the orientation of 30° . *B*: schematic description of a two-alternative-forced-choice (2-AFC) trial in a QUEST staircase for measuring face view discrimination thresholds. Two face views with a slight orientation difference were presented successively. Subjects were asked to make a 2-AFC judgment of the orientation of the 2nd face relative to the 1st face (left or right). *C*: learning curve. Face view discrimination thresholds are plotted as a function of training day. *D*: face view discrimination thresholds plotted as a function of face orientation before training, immediately after training, and 1 and 6 mo after training. *E*: percent improvement in face view discrimination performance at 7 orientations immediately after training and 1 and 6 mo after training. Data were averaged across 8 subjects. Error bars denote SE calculated across subjects.

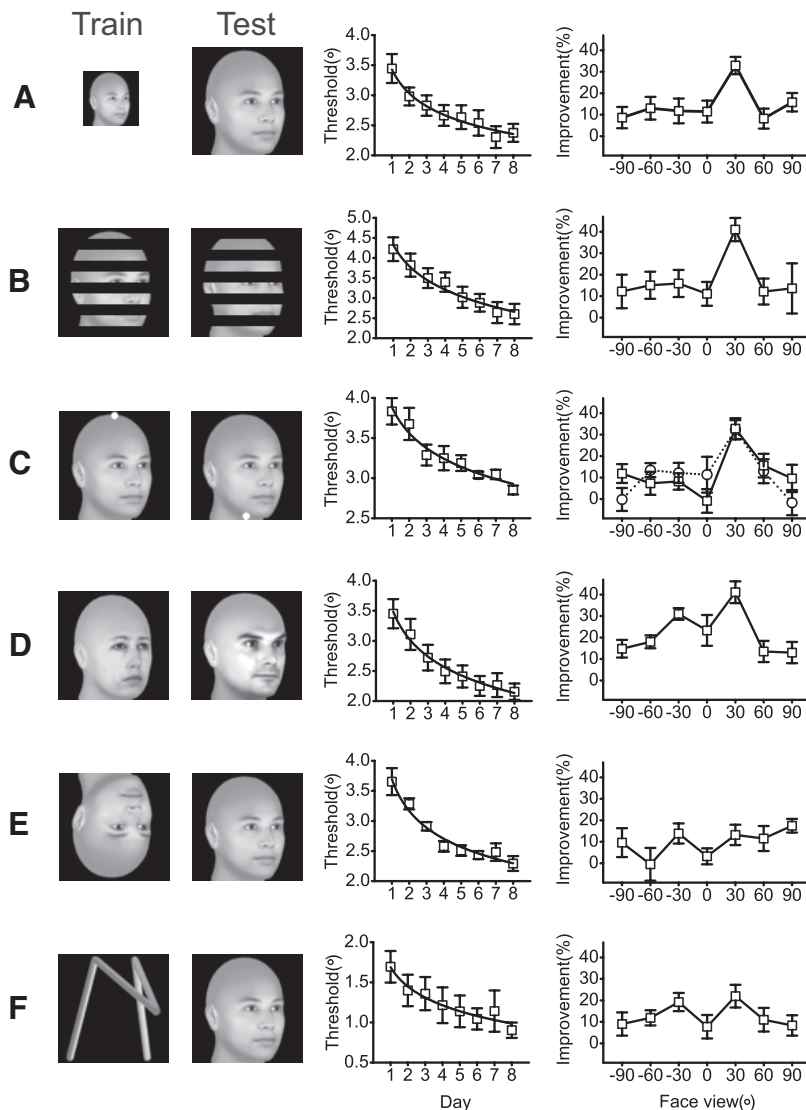


FIG. 2. Transfer of training effect from trained stimuli to test stimuli in *experiments 2–7*. Trained stimuli, test stimuli, learning curves, and percent improvements of face view discrimination performance are presented from *left to right*. *A*: the trained and test faces in *experiment 2* were different in size. *B*: the trained and test stimuli in *experiment 3* were mutually exclusive and constituted a complete face. *C*: in *experiment 4*, the trained and test faces were presented in the lower and the upper visual fields, respectively. The improvements in the lower and the upper visual fields are plotted with a dotted line and a solid line, respectively. *D*: in *experiment 5*, the trained face was Anti-Jim and the test face was Jim. *E*: in *experiment 6*, the trained stimulus was the inverted version of the test face. *F*: in *experiment 7*, the trained stimulus was the M-like paperclip and the test stimulus was the default average face. Learning curves and performance improvements were averaged across subjects. Error bars denote SE calculated across subjects.

was randomized. Their spatial positions were randomly distributed within a $6.2 \times 6.2^\circ$ area whose center was coincident with the fixation point, with a constraint that these two face views were separated by $\geq 1.5^\circ$ of visual angle. Subjects were asked to make a two-alternative-forced-choice (2-AFC) judgment of the orientation of the second face relative to the first face (left or right). A high-pitched tone was provided after a wrong response, and the next trial began 1 s after response. The θ varied trial by trial and was controlled by the QUEST staircase to estimate subjects' face view discrimination threshold (75% correct).

Before and after the 8-day training, we tested subjects' discrimination performance. Their face view discrimination thresholds were measured at the face orientations of -90 , -60 , -30 , 0 , 30 , 60 , and 90° (Fig. 1A). Eight QUEST staircases (same as above) were completed for each orientation and each subject within 2 days. These seven orientation conditions were counterbalanced within individual subjects. Before the experiments, subjects practiced two staircases (80 trials) for each orientation to get familiar with the stimuli and the experiment procedure.

In *experiment 1* (Fig. 1, A and B), we examined the orientation specificity of face view learning and its persistence. The default average face was used for both training and pre-/posttraining tests. Additionally, face view discrimination thresholds were measured 1 and 6 mo after training.

Experiments 2–7 were designed to study the transfer of training between the trained and the test stimuli. In *experiment 2*, the trained and the test faces extended 2×2 and $4 \times 4^\circ$ of visual angle, respectively (Fig. 2A). In *experiment 3*, both the trained and the test stimuli were a partial face (Fig. 2B). They were mutually exclusive and constituted a complete face. They were generated by splitting the default average face into 10 parts with the same size ($0.3 \times 3^\circ$ of visual angle) and leaving the odd-numbered (counted from top to bottom) parts for the trained stimulus and the even-numbered parts for the test stimulus.

In *experiment 4*, face view discrimination was trained in the lower visual field and was tested in both the upper and the lower visual fields. The trained and the test faces were presented in a $6.2 \times 6.2^\circ$ area immediately below and above the fixation point respectively (Fig. 2C). In *experiment 5*, the trained face was Anti-Jim and the test face was Jim (Fig. 2D). In *experiment 6*, the default average face and its inverted version were used as the test and the trained stimuli, respectively (Fig. 2E). In *experiment 7*, the trained stimulus was the M-like paperclip, and the test stimulus was the default average face (Fig. 2F).

Data analysis

For the pre- and posttraining tests, discrimination thresholds from eight QUEST staircases for each of the seven face orientations were

averaged as a measure of subjects' discrimination performance and plotted as a function of orientation. Note that subjects were randomly selected to be trained at either -30° or $+30^\circ$. Because training at the two orientations induced a similar learning effect, for the sake of presentation simplicity, the discrimination performance functions for subjects trained at -30° were flipped horizontally and averaged together with the functions for subjects trained at $+30^\circ$. Subjects' performance improvement at an orientation was calculated as (pretraining threshold - posttraining threshold)/pretraining threshold \times 100%. To measure the time course of the training effect (learning curve), discrimination thresholds from 25 QUEST staircases in a daily training session were averaged and plotted as a function of training day. Learning curves were fitted with a power function (Jeter et al. 2009).

To quantify the transfer of training between the trained and the test stimuli, transfer index was defined as the ratio of performance improvement with the test stimulus and that with the trained stimulus. Performance improvement with the trained stimulus over eight daily training sessions was calculated as (1st day threshold - 8th day threshold)/1st day threshold \times 100%. The test stimulus here had the same orientation as the trained stimulus. Paired *t*-test and independent-samples *t*-test were carried out for within-subject comparisons and between-subject comparisons, respectively.

RESULTS

Perceptual learning in face view discrimination

In *experiment 1*, we first measured subjects' face view discrimination thresholds at seven orientations of -90° , -60° , -30° , 0° , 30° , 60° , and 90° (Fig. 1, A and B). Subjects practiced for 8,000 trials during eight daily training sessions on face view discrimination at the orientation of 30° . Throughout the training course, their discrimination thresholds gradually decreased, which resulted in a 36% performance improvement (Fig. 1C). After training, we measured thresholds at the seven orientations again.

Before training, subjects had a significant lower threshold (better performance) at 0° than the thresholds at other orientations [all $t(7) > 4.7$, $P < 0.01$; gray line in Fig. 1D], which is consistent with the claim that 3D symmetric shapes are discriminated more efficiently than asymmetric ones (Liu and Kersten 2003). After training, the threshold at 30° was comparable to that at 0° [$t(7) = 0.45$, $P = 0.67$] and was significantly lower than those at other orientations [all $t(7) > 4.4$, $P < 0.01$; black line in Fig. 1D]. We calculated the percent improvement in discrimination performance after training. The improvement at the trained orientation of 30° was 44%, which was significantly higher than those (about or $<10\%$) at other orientations [black line in Fig. 1E; all $t(7) > 4.7$, $P < 0.01$]. These results suggest an orientation-specific perceptual learning in face view discrimination.

To examine the persistence of the learning effect, we measured the discrimination thresholds 1 and 6 mo after training (red and green lines in Fig. 1D). Relative to the performance before training, the percent improvements in discrimination performance at the trained orientation of 30° was 34% 1 mo after training and 33% 6 mo after training (red and green lines in Fig. 1E). This means that the learning effect was long-lasting, and 75% of the effect was kept after a half-year break. It is noteworthy that the learning effect persisted in an orientation-specific manner. The improvements at the untrained orientations were around or $<10\%$, which were significantly

lower than the improvement at 30° [all $t(7) > 3.5$, $P < 0.01$, except the marginal significance at 90° 6 mo after training, $t(7) = 2.1$, $P = 0.077$]. The long-lasting orientation-specific perceptual learning in face view discrimination was quite robust and consistent across individual subjects.

Transfer of the face learning effect

Experiments 2-7 were designed to study the transfer of training from trained stimuli to test stimuli. The test stimuli were always faces. The trained stimuli shared more or less properties with the test stimuli. Similar to *experiment 1*, subjects underwent eight daily training sessions to discriminate views of the trained stimulus at the orientation of 30° . Before and after training, we measured subjects' face view discrimination thresholds with the test stimulus at the seven orientations of -90° , -60° , -30° , 0° , 30° , 60° , and 90° .

Experiment 2 studied how a size change from the trained stimulus to the test stimulus could affect the transfer of learning (Fig. 2A). The area of the test stimulus was four times that of the trained stimulus. The 8-day training resulted in a 31% improvement in discrimination performance with the trained stimulus at the orientation of 30° . Relative to the performance before training, the improvement after training with the test stimulus at 30° was 33%, significantly higher than the improvements at the untrained orientations [all $t(7) > 2.5$, $P < 0.05$].

Experiment 3 investigated the effect of face part change on the transfer of learning. The trained and the test stimuli were mutually exclusive, and they constituted a complete face (Fig. 2B). Throughout the training course, subjects' discrimination thresholds gradually decreased, which resulted in a 38% performance improvement with the trained face. Relative to the pretraining performance, the improvement after training with the test face at 30° was 41%, significantly higher than the improvements at the untrained orientations [all $t(5) > 3.1$, $P < 0.05$].

In *experiment 4*, the trained face was presented in the lower visual field, and the test face was presented in either the lower or the upper visual fields (Fig. 2C). The objective of the experiment was twofold. First, *experiments 1-3* showed that face view learning could take place around the fixation point. Here we examined if the learning could occur at a more eccentric area, e.g., the lower or the upper visual field. Second, we were interested in the effect of visual field change on the transfer of learning. Similar to *experiments 1-3*, eight training sessions in the lower visual field led to a 27% performance improvement. Before and after training, we measured face view discrimination thresholds in both the lower and the upper visual fields. Subjects' performance improvements at the trained orientation were 33 and 32% in the lower and the upper visual fields, respectively, both of which were orientation specific [lower visual field: all $t(5) > 2.6$, $P < 0.05$, dotted line; upper visual field: all $t(5) > 3.3$, $P < 0.05$, solid line].

Experiment 5 examined the effect of face identity change on the transfer of learning (within-category transfer). The trained face was Anti-Jim and the test face was Jim (Fig. 2D). They were a face/anti-face pair, which lay at the two ends of a face identity trajectory (Leopold et al. 2001). After eight daily training sessions, subjects' performance with the trained face improved by 37%. We also found that the learning transfer was

orientation specific because the improvement with the test stimulus at 30° was 41%, significantly higher than those at the untrained orientations [all $t(6) > 2.5$, $P < 0.05$].

In *experiments 6* and *7*, the test stimulus was a face and the trained stimuli were an inverted face (Fig. 2E) and an M-like paperclip (Fig. 2F). Here we examined how face inversion and object category change affected the learning transfer. Similar to the training effect with an upright face, training with the inverted face and the paperclip at the orientation of 30° also improved subjects' discrimination performance by 36 and 45%, respectively. However, compared with *experiments 2–5*, the performance improvements with the test face at 30° were weak (13 and 22%). These improvements were not orientation-specific because there was no significant difference between the trained orientation and the untrained orientations [inverted face: all $t(6) < 1.9$, $P > 0.12$; paperclip: all $t(7) < 2.3$; $P > 0.07$].

To quantify the transfer of training between the trained and the test stimuli, the transfer index was calculated as the ratio of performance improvement with the test stimulus and that with the trained stimulus (Fig. 3). A large index means that a large amount of the training effect has been transferred to the test stimulus; in other words, the performance improvement with the test stimulus can be largely attributed to the training effect. The transfer indices in *experiments 1–5* were 1.23, 1.12, 1.06, 1.27, and 1.18. There was no significant difference among them [$F(6,50) = 1.176$, $P = 0.336$]. Note that, in *experiment 1*, the test and the trained stimuli were the same. These results suggest a complete transfer from the trained stimulus to the test stimulus in *experiments 2–5*. Why are the indices larger than 1? This is because the threshold measurement before training also led to some learning effect. The transfer indices in *experiments 6* and *7* were 0.37 and 0.54, respectively. There was no significant difference between them ($t = 0.85$, $P = 0.41$). However, they were significantly lower than the indices in

experiments 1–5 [$F(8,65) = 5.616$, $P < 0.001$], which suggests a partial or weak transfer in *experiments 6* and *7*.

DISCUSSION

We see faces from various viewing angles every day. Face view perception informs us not only about a person's identity but also about his/her social attention. Even from a small face view change, we could infer changes in their current goals and intentions (Nummenmaa and Calder 2009). Can our ability of face view perception (discrimination) be improved with training? In this study, a series of seven experiments was conducted to address this question and to investigate the characteristics of perceptual learning of face view discrimination. *Experiment 1* showed that training led to a significant improvement in sensitivity to face view orientation. The improvement was highly specific to the trained orientation and lasted up to 6 mo. In *experiments 2–5*, we found that the orientation-specific learning effect completely transferred across changes in face size, visual field, and face identity. A complete transfer also occurred between two partial face images that were mutually exclusive but constituted a complete face. However, the transfers were weak between an upright face and an inverted face and between a paperclip object and a face, as shown in *experiments 6* and *7*. It should be noted that, in most experiments, only one face stimulus was used. These conclusions can be further strengthened if more face stimuli were used.

Face view learning exhibited two important characteristics of perceptual learning: specificity and persistence (Liu 1999; Sasaki et al. 2010). Training at 30° had a very weak effect on the discrimination performance at other orientations, even at 0 and 60°. It could be argued that subjects' view sensitivity at 0° (cardinal orientation) was already very high, leaving little room for improvement. To rule out the explanation, we trained two subjects using the same procedure as that for 30°. The training

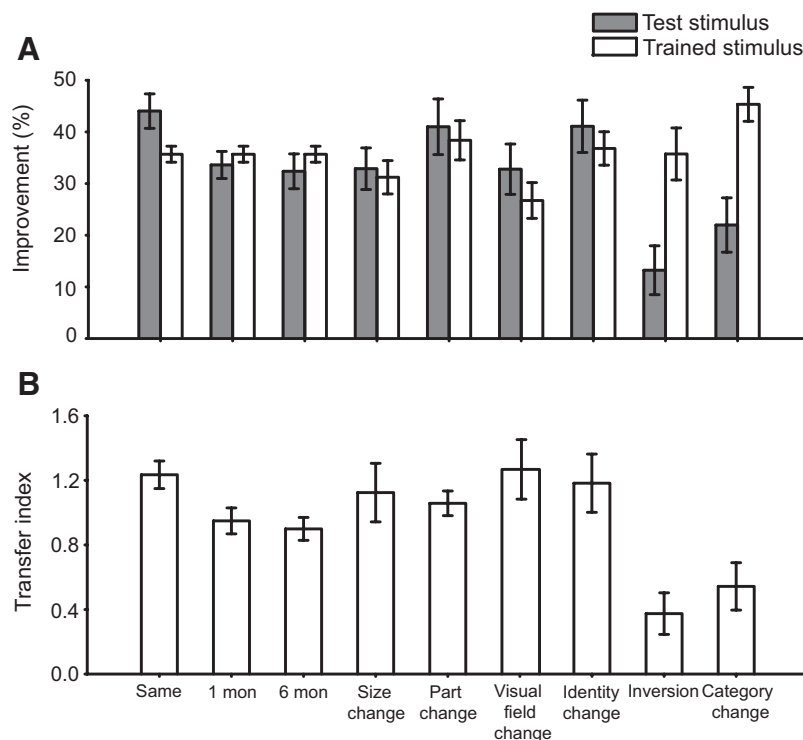


FIG. 3. *A*: performance improvement with trained and test stimuli in *experiments 1–7*. *B*: transfer index of training effect from trained stimuli to test stimuli in *experiments 1–7*.

resulted in a 48% performance improvement at 0°, comparable to the training effect at 30°. It has been reported that some face neurons in STS responded symmetrically to left and right views (De Souza et al. 2005). This would predict that training at 30° should also lead to a higher performance improvement at -30° than at 0, ±60, and ±90°. However, we did not find such an effect, which indicates that training might have a very weak or little influence on these STS neurons. The benefits of perceptual learning with visual features are usually long-lasting, persisting for up to 2 yr (Karni and Sagi 1993). In high-level vision, training effects with a shape/object identification task could last 1 mo (Furmanski and Engel 2000; Sigman and Gilbert 2000). Here, we expanded these results by showing that the orientation-specific face view learning could last ≤6 mo.

Using a visual search or identification task, past studies indicated that face/shape recognition is subject to perceptual learning (Furmanski and Engel 2000; Golcu and Gilbert 2009; Hussain et al. 2009; Sigman and Gilbert 2000). However, few of them studied the characteristics of high-level visual perceptual learning as comprehensively as this study. There are two similar findings in previous studies and ours. One is the complete transfer across a change in face size, in agreement with the finding that object learning was insensitive to image size (Furmanski and Engel 2000). The other is the weak transfer from an upright face to its vertical inversion. Hussain et al. (2009) also found that face identification training was largely specific to the in-plane orientations of trained faces. Both studies suggest that the neural codings of upright faces and inverted faces are quite different. However, a significant contrast between past studies and ours is whether learning was restricted to the area where the stimulus was trained. Our study showed a complete transfer from the lower visual field to the upper visual field. Such a transfer between visual fields was not found in other studies (Cox and DiCarlo 2008; Dill and Fahle 1997; Nazir and O'Regan 1990). Two noteworthy points can explain the discrepancy. First, in these studies, subjects were trained to identify simple shapes that can be coded by retinotopic areas (e.g., V2 and V4; Hedge and Van Essen 2007). Second, these shapes were trained at a fixed position in the visual field. The face stimuli in our study were randomly presented in a small area, which might subserve the spatial transfer of the learning effect.

Where does face view learning occur in the visual cortex? In the human visual cortex, there are three face-selective areas: OFA, STS, and FFA (Fang et al. 2007; Haxby et al. 2000), which are the possible loci of the learning. Also, a recent study (Sigman et al. 2005) suggested that retinotopic areas played an important role in high-level visual perceptual learning with a shape identification task. By measuring the transfer of learning from the trained face to other visual stimuli more or less resembling it, we can infer where face view learning took place in the visual system and what was learned during training. First, the complete transfers across changes in face size, face part, and visual field could rule out early retinotopic areas and OFA. Because the receptive fields of neurons in early retinotopic areas are small (Smith et al. 2001), they are sensitive to stimulus changes in size, local feature, and position in the visual field. Although OFA is at a higher position in the visual processing hierarchy than early retinotopic areas, it is still retinotopically organized (see a review by Wandell et al. 2007) and is sensitive to changes in face part (Pitcher et al. 2007). Thus the properties of early retinotopic areas and OFA do not support the

complete transfers we observed. Second, the complete transfer of the learning from a face to its anti-face suggests that the learning effect is identity invariant, which resonates with the finding that most view-selective face neurons in macaque STS are not sensitive to identity (Perrett et al. 1992). Using fMRI adaptation, Fang et al. (2007) showed that both STS and FFA in human visual cortex could encode face views. However, Grill-Spector et al. (2004) showed that FFA, but not STS, is selective for face identity. Thus STS is more likely to be the cortical locus of face view learning than FFA. Third, the weak transfers from the trained face to its in-plane inversion and to the paperclip object can rule out an alternative explanation that the face view discrimination learning is a general 3D orientation discrimination learning and takes place at cortical areas coding 3D orientation. Hinkle and Connor (2002) reported that some neurons in macaque area V4 carry robust signals for 3D orientation defined by binocular disparity. Although the orientation of the face views was not defined by disparity, the finding by Hinkle and Connor does suggest the alternative explanation for our observation. A key prediction of this 3D orientation learning explanation is that it should not depend on the object representation in the visual system, as long as the trained and the test stimuli are in the same 3D orientation. In our study, however, only weak transfers were observed, even though both the inverted face and the paperclip object as the trained stimuli (Bi et al. 2009; Fang and He 2005) have the same orientation as the test face. Taken together, converging evidence suggests that training on face view discrimination resulted in a large amount of plastic changes at a level of higher visual processing where size-, position-, and identity-invariant face views are represented.

Our results suggest that what was learned by the visual system during training is the improved ability of computing face orientation from the configural information of face views, rather than the configural information itself or face parts. Another recent study, on the other hand, suggests that objects are learned in a parts-based manner (Golcu and Gilbert 2009). This superficial contradiction can be easily explained. In the study of Golcu and Gilbert, objects were composed of three line segments, each of which could provide diagnostic information for accomplishing object recognition. In our study, although local features in face views could provide more or less information about face orientation, it might be more reliable to extract the orientation from the configural information, especially when the face views were randomly presented in a small area. Indeed, both studies support the claim that perceptual learning drives the visual system to extract the regularities of the environment and develop optimal strategies for visual information processing (Gilbert et al. 2001).

Visual perceptual learning studies have led to an increasing understanding of plasticity in the adult visual system. This study developed a powerful experimental protocol to study high-level visual perceptual learning and shown the characteristics of face view learning. It is time to use brain imaging and single-unit methods to study the neural mechanisms of face view learning and therefore open the window into one of the central questions in vision sciences—plastic object representation in the visual system.

ACKNOWLEDGMENTS

We thank S. He for helpful discussions and D. Leopold for providing the face images with different identities.

GRANTS

This work was supported by the National Natural Science Foundation of China (Projects 30870762, 90920012, and 30925014) and the Ministry of Science and Technology of China (2010CB833903).

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

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