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Perceptual Learning Solely Induced by Feedback

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Abstract

Although feedback is considered to be an important factor in perceptual learning (PL), its role is normally considered limited to facilitation, rather than direct inducement, of PL. Recent studies, however, have suggested feedback to be more actively involved in the inducement of PL. The current study demonstrates an even more significant role for feedback in PL: feedback can evoke PL of a feature without any bottom-up processing of that feature. We use a "fake feedback" method, in which the feedback is related to an arbitrarily chosen feature, rather than actual performance. We find evidence of PL with this fake feedback method both when the learned feature is absent from the visual stimulus (Experiment 1) and when it conflicts with the visual stimulus (Experiment 2). We call this "feedback-based PL," in contrast with the classical "exposure-based PL." We find that feedback-based PL and exposure-based PL can occur independently of each other even while occurring in the same paradigm. These results suggest that feedback not only facilitates PL that is evoked by bottom-up information, but that it can directly induce PL, where such feedback-based PL occurs independently of exposure-based PL.

Keywords

perceptual learning; feedback; fake feedback

1. Introduction

Perceptual learning (PL) is defined as long-term performance enhancement on a perceptual task as a result of perceptual experience. A number of studies have indicated the importance of top-down processing in PL. Attention, for example, has been shown to play a critical role in PL. Specifically, focused attention to a task-relevant feature is crucial for PL of that feature (e.g. Ahissar & Hochstein, 1993), while attention to a task-irrelevant feature inhibits PL of that feature (Choi, Seitz & Watanabe, 2009).

Similarly, response feedback, which notices the correctness of a subject's response, is considered to be an important factor in PL. When valid feedback is given, the performance on a perceptual task is much better than when no feedback is given (Herzog & Fahle, 1997). In addition, successful performance on a task has been shown to lead to PL, showing that reinforcement from internal rewards can boost learning (Sasaki, Náñez & Watanabe, 2010; Seitz & Dinse, 2007; Seitz & Watanabe, 2003; 2005). Despite the demonstrated importance of response feedback, its role in PL is normally considered to be limited to facilitation, rather than direct inducement, of PL, since previous studies have shown that PL can occur without feedback (Karni & Sagi, 1991; Poggio, Fahle, & Edelman, 1992; Watanabe, Náñez & Sasaki, 2001)[1]. More recent studies have suggested, however, that feedback is actively

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[1]However, even the researchers of these results do not deny the importance of feedback in PL.

involved in the formation of PL. Herzog and Fahle (1997), for instance, use a "fake feedback" method to show that feedback can inhibit PL. Their method is one of providing feedback that is not based on actual performance. In the Herzog and Fahle's study, when subjects are given this fake feedback, PL does not occur, suggesting that fake feedback hinders PL. Another study by Shibata and his colleagues alters Herzog and Fahle's fake feedback method to falsely indicate a level of performance that is higher than the subject's actual performance. In this version of the fake feedback method, PL was shown to be facilitated by the fake feedback, in comparison with valid feedback (Shibata, Yamagishi, Ishii & Kawato, 2009).

The central question of this paper concerns the role of feedback in PL: How significant is the influence of feedback in PL? In particular, we explore whether feedback can induce PL of a feature without the feature being presented at all.

2. Experiment 1

We first tested whether feedback can induce PL when the presented stimulus is absent of all relevant information. During training, subjects were asked to identify the orientation of sinusoidal gratings by choosing one of two alternative choices (orientations "A" and "B"). In half of the trials, gratings with orientation A were presented, followed by valid feedback (valid-feedback trials). That is, if subjects correctly chose orientation A they were given positive feedback, whereas if they incorrectly chose orientation B they were given negative feedback. In the other half of the trials, a "noise" stimulus was presented instead of an actual grating. Despite the absence of a relevant stimulus, feedback was provided in these trials as though orientation B had been presented (fake-feedback trials). In other words, if subjects chose orientation B they were given positive feedback, but if they chose orientation A they were given negative feedback.

Before and after five days of training, the subjects performed a grating detection task, which was not identical to the orientation identification task used in the training sessions. The performance was measured for three orientations. In addition to the two trained orientations, A and B, a new orientation, "C," that was not used during training, was employed as a control (see Figure 1).

2.1. Method

2.1.1. Subjects—Six university students from the Boston area participated in this experiment, all six of which were paid for their participation. All subjects had normal or corrected-to-normal visual acuity and were naïve to the purpose of the study. All subjects signed a consent form approved by the Internal Review Board of Boston University.

2.1.2. Apparatus—The experiment was constructed using Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) for MATLAB (MathWorks, Natick, MA) on a Mac G5 computer. All displays were presented on a 19" CRT monitor, with a resolution of 1280 × 1024 pixels and a refresh rate of 85 Hz. The subjects were positioned approximately 56 cm from the monitor such that the display subtended 36° by 27° of visual angle. A chin rest was used to fix the subject's head position. The experiment was conducted in a darkened room.

2.1.3. Stimulus—The employed stimulus was a sinusoidal grating patch, in which an oriented sinusoidal grating of one cycle per degree, was superimposed on a background filled with spatial white noise. This grating patch was generated by the spatial integration of this sinusoidal grating and noise. Specifically, a number of "signal" pixels were imported from the grating image and the other "noise" pixels were imported from the spatial white noise image to create the sinusoidal grating patch. The signal-to-noise ratio of the grating patch (SN) was manipulated by varying the proportion of signal pixels out of the total number of pixels. SN was thereby varied from 1% to 7% in seven steps. The spatial white noise image was generated to match the sinusoidal luminance distribution so that the gratings and noise could not be distinguished by luminance. The grating patch was presented at the center of the screen, subtending 10° of visual angle. The grating was oriented at 15°, 75° or 135° according to the standard pole coordinates.

2.1.4. Procedures—Experiment 1 consisted of one pre-test session, five training sessions, and one post-test session. The experiment took place over seven days, with one session per day. The subjects were not allowed to suspend sessions for longer than two successive days.

2.1.4.1. Pre- and post-test: For the pre- and post-tests, orientation detection was measured using a two-interval forced choice (2IFC) detection task. The subjects started each trial by pressing a key on the keyboard in front of them. A fixation point (a white dot) was then presented at the center of the screen for 400ms followed by two intervals (each of which was presented for 200ms) with a 400ms gap between the two intervals. In one interval a grating patch was presented, while in the other interval a noise image was presented. Subjects were asked to report which interval contained the grating, irrespective of its orientation. The SN of these grating patches was varied from 1% to 7%, as described in 2.1.3.

In the pre- and post-tests we measured performance for three orientations: (1) the valid-feedback orientation, which matched to the orientation employed in the valid-feedback trials during training, (2) the fake-feedback orientation, which was matched to the orientation employed during the fake-feedback trials in training, and (3) the control orientation, which was not employed during training. As stated in 2.1.3, the orientations we employed in this experiment were 15°, 75° and 135°, where these were assigned to valid-feedback, fake-feedback, or control in a counterbalanced manner.

The subjects first completed a small number of practice trials (24 trials), the data from which are excluded from our analysis. In order to minimize the possibility that learning could occur during practice trials, the grating patches had a high SN (40%) compared to that used in the test sessions (where the SNs were varied from 1% to 7%). After the practice session was over, subjects completed 40 trials in each of the conditions, for a total of 840 trials (3 Orientations X 7 SNs X 40 trials). All the trials were presented in a random order.

2.1.4.2. Training: Unlike the 2IFC detection task in the pre- and post-tests, during training the subjects were asked to identify the orientation of the grating patch. After the presentation of a fixation point, a grating patch was presented in the center of the screen for 200ms. The subjects were asked to report the perceived orientation of the grating by choosing the arrow that represented that orientation using a mouse cursor (a two-alternative forced choice, or “2AFC”). Upon choosing the arrow, feedback concerning the correctness of the response was provided.

In this 2AFC design, subjects were always presented with two optional orientations (orientations A and B), both of which had fixed values throughout the training sessions. These two orientations were exclusively employed in the following two types of trials: orientation A was used only in the valid-feedback trials and orientation B was used only in the fake-feedback trials.

In the valid-feedback trials, grating patches with a 3% SN were presented. These patches had orientation A, so the subjects were given positive feedback when they chose the arrow representing this orientation and negative feedback when they chose the other orientation, orientation B.

In the fake-feedback trials, on the other hand, noise images with 0% SN were presented. Although the stimuli in these fake-feedback trials had no orientation information, the feedback was given as if the stimulus had orientation B. That is, subjects were provided with positive feedback if they chose Orientation B and negative feedback if they chose Orientation A.

Because 3% SN grating patches are difficult to be detected, the subjects were unable to distinguish these two types of trials from the differences in signal strength. Moreover, the subjects were told that all stimuli had 3% SN. During an interview session after experiment completion, the subjects reported that they did not recognize the presentation of noise patches.

Feedback was provided through both the visual and auditory modalities. The word “Correct” combined with a low-pitched sound indicated that the subject responded correctly, whereas the word “Wrong” combined with a high-pitched sound indicated that the subject had responded incorrectly.

In each training session, the subjects completed 500 trials per feedback type in random order for a total of 1000 trials a day, which took approximately one hour to complete. As stated above, only one training session was conducted per day. Five days were required to complete the training.

2.2. Results and discussion

The percentage of trials in which the subjects detected the grating patches correctly for each SN in the pre- and post-tests is shown in Figure 2. A three-way repeated measure ANOVA (orientation, training, and SN) revealed a significant effect on SN ($F(6,30) = 197.818$, $p < .001$), but no significant effect on training ($F(1,5) = 4.799$, $p = .080$) or orientation ($F(2,10) = 0.578$, $p = .579$). In addition, there were significant interaction effects 1) between training and SN ($F(6,30) = 4.325$, $p = .003$) and 2) between training and orientation ($F(2,10) = 7.057$, $p = .0123$). The significant interaction between training and orientation implied that our training resulted in a different learning effect for each orientation. In order to determine which orientation(s) resulted in performance improvement after training, a posthoc t-test was conducted for each orientation with the mean percentage of trials involving correct responses across all SNs. Subject performance in the post-test improved significantly not only for the valid-feedback orientation ($t(5)=4.045$, $p = .009$) but also for the fake-feedback orientation ($t(5)=2.5849$, $p = .049$). However, this learning effect was not observed for the control orientation ($t(5)=1.508$, $p = .191$).

These results show a significant improvement in performance on the fakefeedback orientation after training. However, this improvement might be due to an improved sensitivity to noise. Recall that during training a noise patch was presented to subjects in half of the trials. These repeated presentations might have induced an improved sensitivity to the noise stimulus itself. Improved sensitivity to noise could have resulted in better performance in the 2IFC test because the subjects would then have noticed more successfully which interval contained only noises and could then have chosen the other interval as their response. Against this alternative explanation, no improvement was observed for the control orientation in the 2IFC task. If sensitivity to noise improved after training, the performance on the control orientation should also have been improved. Therefore, we conclude that the improved performance in the 2IFC test is not due to an improved sensitivity to noise.

The improved performance on the fake-feedback orientation might be due to an induced association between that orientation and increased noise, since the fakefeedback orientation was associated with 0% SN instead of the 3% SN associated with the valid-feedback orientation. The subjects might simply respond with the fake-feedback orientation whenever they observe an ambiguous stimulus with a low SN. However, if this explanation were correct then such an association should have brought about a decrease in performance for this orientation in the 2IFC tests, as opposed to an increase, since the 2IFC task requires the subject to identify signal from noise (i.e. the grating image from the noise image).

Thus, we conclude that feedback can actively evoke PL of a feature even when that feature is not actually presented in the stimulus.

3. Experiment 2

The results of Experiment 1 suggest that response feedback plays a critical role in PL by showing that PL can be induced by feedback even without the presentation of the learned feature. Feedback-based PL seems to be crucially different from exposure-based perceptual learning (EBPL) in this respect. A number of EBPL studies have indicated that PL of an exposed feature occurs without either attention to that feature or response feedback, so long as reinforcement signals are given while the feature is presented (Seitz & Watanabe, 2003, 2005, 2009).

Whereas EBPL of a feature requires the presentation of that feature but not response feedback, feedback-based PL needs response feedback but not feature presentation. These opposing requirements bring up an interesting question about the relationship between feedback-based PL and EBPL: can feedback-based PL be induced independently of EBPL?

In Experiment 2, we tested whether feedback-based PL was influenced by the processing of contradictory bottom-up information. As in Experiment 1, two types of trials were employed, the valid-feedback trials and the fake-feedback trials. The procedure of the valid-feedback trials in Experiment 2 was identical to that of the valid-feedback trials in Experiment 1. Namely, during training subjects were asked to report which of two alternative orientation choices (orientations A and B) represented the previously presented 3% SN grating patch (with orientation A). In the fake-feedback trials, in contrast to Experiment 1, a 3% SN grating patch was presented instead of a noise patch. The orientation of this grating patch (orientation C) was not presented on the response display as one of the two optional orientations (orientations A and B). Although orientation C was presented as the stimulus, the response feedback was centered around the selection of orientation B. That is, the subjects were given positive feedback if they chose orientation B and negative feedback if they chose orientation A (see Figure 3). This “fake feedback” allowed us to examine whether feedback-based PL interacts with EBPL by comparing PL for the presented or “signal” orientation, the “feedback” orientation, and the “signal+feedback” orientation presented in the valid-feedback trials. Any PL found for orientation C would be categorizable as EBPL, since such learning could only be induced by the presentation of that orientation in the stimulus (without any response feedback). Any PL found for orientation B, on the other hand, would be categorizable as feedback-based PL that took place through fake feedback.

Before and after five days of training, we measured performance on a grating detection task with three orientations: 1) the signal+feedback orientation (orientation A), 2) the feedback orientation (orientation B) and 3) the signal orientation (orientation C).

3.1. Methods

Six new subjects participated in this experiment. Experiment 2 employed similar stimuli and procedures to those employed in Experiment 1, with the exceptions described above.

3.2. Results and discussion

The percentage of correctly detected grating patches in the pre- and posttests is depicted in Figure 4 for each SN. In order to explore the potential independence of feedback-based PL from EBPL, a three-way repeated measure ANOVA (orientation, training, and SN) was conducted. There were significant effects of training ($F(1,5) = 11.928$, $p=.018$) and SN ($F(6,30) = 26.861$, $p<.001$), while no effect of orientation was found ($F(2,10) = 0.597$, $p=.569$). In addition, no significant interaction, particularly between orientation and training ($F(2,10) = 1.186$, $p=.345$), was observed.

These results show that PL was induced both by top-down information (response feedback) and by bottom-up information (stimulus signal). The absence of significant interaction in a three-way ANOVA implies that these two kinds of learning do not inhibit each other. This suggests that feedback-based PL is not influenced by the processing of contradictory bottom-up signals and occurs independently of EBPL.

4. General Discussion

In the current study we examined the role of feedback in PL. A number of previous studies have shown that PL can occur without feedback (e.g. Karni & Sagi, 1991) and have implied that feedback is involved in facilitation, rather than direct inducement, of PL. However, our results show that feedback signals can evoke PL of a stimulus without that stimulus being presented and that such feedback-based PL occurs independently of EBPL.

4.1 Can fake feedback evoke PL?

We owe the finding of feedback-based PL to the fake feedback method, in which feedback does not reflect accuracy of response but is centered around a pre-determined feature value. A previous study has indicated that although fake feedback changes the subjects' response patterns, the changes are not a result of substantial changes in the visual system (Herzog & Fahle, 1999; see also Herzog, Ewald, Hermens, & Fahle, 2006). This study comprised a vernier discrimination task where the subjects were first asked to report the direction of the vernier offset between two line segments, leftward or rightward, and were then given fake feedback in certain trials. Namely, the subjects were given fake feedback when the verniers had a small offset of one direction (e.g. leftward) that indicated the offset was in the opposite direction (e.g. rightward). Valid feedback was provided for the other trials. After this vernier training, a significant effect from fake feedback was observed: the subjects showed poor performance for the fake feedback offset direction (e.g. the leftward offset). However, this effect disappeared immediately when valid feedback was instead given for the fake feedback offset direction. The temporary nature of the drop in performance suggests that fake feedback evokes changes in the internal decision criteria, rather than in the visual system

This result seems inconsistent with the findings of the current study, which shows that PL, rather than a temporary criterion shift, can be induced by fake feedback. However, the difference between these findings may result from the fact that these two studies focus on different potential roles for feedback-based PL. Herzog and Fahle's study explores whether feedback-based PL can *change* the perception of the bottom-up signals and finds that subjects do not, in fact, perceive changes in the stimulus based on fake feedback (e.g. they do not perceive a small leftward offset as a small rightward offset as a result of fake feedback). *improve* the subject's perception of the indicated feature (i.e. the current study investigates whether the subject's detection of that feature is improved by training with fake feedback).

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In order to explore whether feedback-based PL is perceptual or not, it would be interesting to check whether the improvement induced by fake feedback is retained in the long term. Since the durability of learning improvements is one of main features of PL, as reported in many previous studies (e.g. Karni & Sagi, 1991), the result of such long-term study would clarify the issue of whether or not feedback-based PL influences visual perception.

In addition, it may be argued that the improvement for the feedback orientation is due to just repetitive performance of the given task, rather than the feedback itself. Although the feedback orientation was not presented in a given stimulus, it was one of two optional orientations on the response display, which was then chosen as a correct answer by the subjects (regardless of whether it was actually correct or not). This repetitive involvement of the feedback orientation in the subjects' response might induce improvement in the performance. The answer to this issue will be obtained through an experiment that is identical to Experiment 1, except no response feedback will be provided.

4.2 Feedback-based vs. imagination-based PL

Previous studies have shown that imagination can evoke PL of a feature even without any bottom-up information about that feature (Dupuis-Roy & Gosselin, 2007; Tartaglia, Bamert, Mast & Herzog, 2009). Although both imagination-based learning and our feedback-based learning demonstrate that PL can be induced solely by top-down processing, these two types of PL have several differences.

First, in studies of imagination-based PL, subjects have to imagine a feature that is not presented and must thus be made aware that the feature is absent from the presented stimulus. In the current study, on the other hand, subjects were neither instructed that the relevant feature was absent from the stimulus nor were they aware that the relevant feature was absent.

Second, while in studies on imagination-based PL top-down information (i.e. what the subjects were supposed to imagine) was provided before the subjects viewed a noise display, in the current study feedback was given after the presentation of a noise display. Thus, while both types of learning are based solely on top-down signals, their mechanisms may not be identical.

4.3 Future studies of feedback-based PL

The current study shows that PL of a feature can occur even if the feature is not presented during training so long as that feature is indicated by feedback. The absence of bottom-up processing in the formation of PL gives rise to the possibility that feedback-based PL has different characteristics from standard PL. Standard PL shows strong specificity, for example. This is illustrated in task-irrelevant PL, where PL occurs only for the orientation exposed during training and not for other orientations (Watanabe et al., 2001). PL induced by imagination, however, demonstrates weak specificity, such that the learning can be transferred, for instance, to an untrained stimulus rotated by 90° from the trained stimulus (Tartaglia et al., 2009). This result gives rise to the possibility that feedback-based PL will show weak specificity. These and other characteristics of feature-based PL should be explored in more detail in future studies.

Any future studies that compare the characteristics of feedback-based PL with other types of PL should take care to induce PL through training conditions that are as similar to each other as possible. In Experiment 2 of our study we found that both feedback-based PL and EBPL occurred with a single training task, and that these two types of learning occurred independently. This advantage, that the two types of PL can be induced independently by a single training task, will likely aid further exploration of the characteristics of feedback-based PL.

5. Conclusions

It has been suggested that feedback is not involved in the formation of PL but in its facilitation, since PL can occur without any feedback. Using the fake feedback method, the current study demonstrates that PL can be evoked solely by feedback both when the relevant feature is absent from the stimulus and when the learned feature conflicts with the relevant feature presented in the stimulus. Further, this study indicates that such learning can occur without significant interaction between EBPL and feedback-based PL in the case that the learned feature and the presented feature conflict. Our results suggest that these two types of PL can occur independently, each involving their own underlying mechanism.

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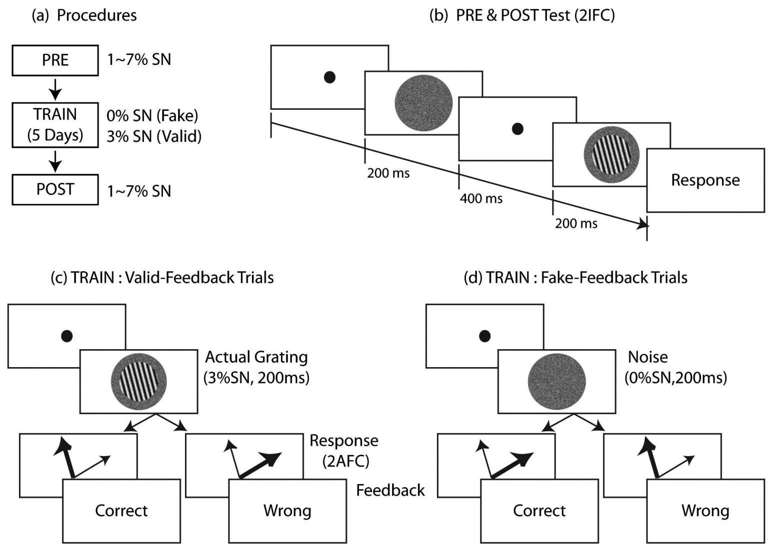

Figure 1.

An illustration of the procedure in Experiment 1. (a) Outline: The experiment consisted of a pre-test session, five training sessions, and a post-test session, in that order. (b) Task procedure in the pre- and post-test sessions: The subjects were asked to report which of the two intervals included an oriented grating patch (a 2IFC task). The SN was varied in 7 steps (1% to 7%). The orientation in the patch was 15°, 75° or 135°. (c) Task procedure during the validfeedback trials in training: The subjects were asked to identify the orientation of a grating patch with a 3% SN by choosing one of the two arrows that might represent that orientation. Valid feedback was provided after a subject’s response. (The bolded arrow on the response display in the image represents the subjects’ choice.) (d) Task procedure during the fake-feedback trials in training: The procedure was identical to that of the valid-feedback trials, except that a noise patch was presented instead of an oriented grating. Although there was no correct answer, the subjects were given positive feedback if they selected a pre-determined orientation. See the text for detailed information. (The bolded arrow on the response display in the image represents the subjects’ choice.)

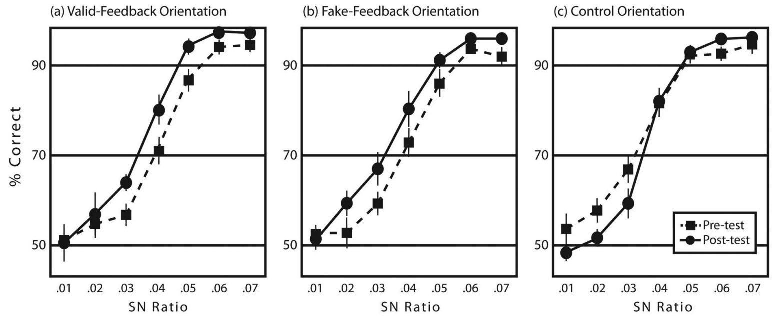

Figure 2.

The mean percentage of correctly detected grating patches in the 2IFC task, organized by SN, for: (a) the valid-feedback orientation, the orientation which was employed in the valid-feedback trials during training sessions, (b) the fakefeedback orientation, the orientation which was employed in the fake-feedback trials, and (c) the control orientation, an orientation that was not employed during training.

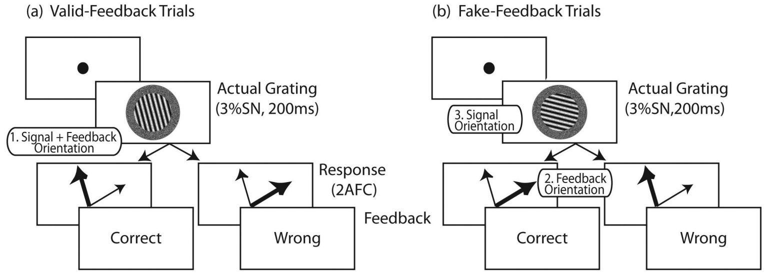

Figure 3.

An illustration of the task procedure in Experiment 2 for: (a) the validfeedback trials and (b) the fake-feedback trials. Although the task procedure in the valid-feedback trials was identical to that of Experiment 1, the task procedure in the fake-feedback trials involved an actual grating with 3% SN (unlike Experiment 1). Even though the presented orientation in the fake-feedback trials was not one of the two alternative orientations available on the response display, the subjects were given positive feedback if a pre-determined orientation was chosen. Each subject’s performance was measured both before and after training on three orientations, indicated in the figure: (1) the signal+feedback orientation employed in the validfeedback trials, (2) the feedback orientation that was pre-determined as the correct answer in the fake-feedback trials, and (3) the signal orientation that was actually presented in the fake-feedback trials. (The bolded arrow on the response display in the image represents the subjects’ choice.)

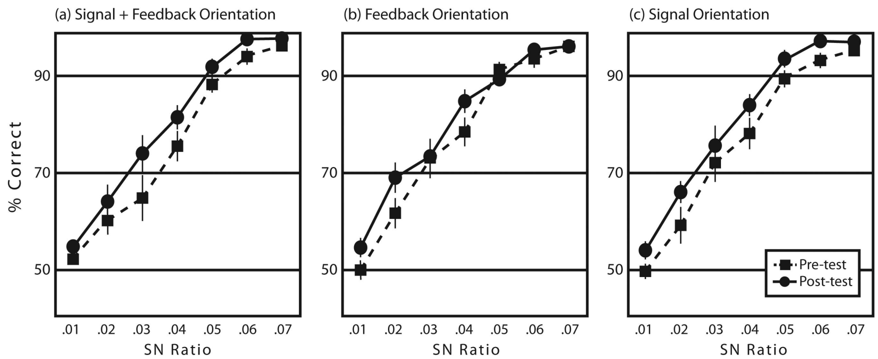

Figure 4.

The mean percentage of correctly detected grating patches for: (a) the signal+feedback orientation, the orientation that involved both a stimulus and response feedback in the valid-feedback trials, (b) the feedback orientation, the orientation that was pre-determined as the correct answer in the fake-feedback trials, and (c) the signal orientation, the orientation that was presented as the stimulus in the fake-feedback trials.