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Perceptual learning and attention: Reduction of object attention limitations with practice

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ABSTRACT

Perceptual learning has widely been claimed to be attention driven; attention assists in choosing the relevant sensory information and attention may be necessary in many cases for learning. In this paper, we focus on the interaction of perceptual learning and attention – that perceptual learning can reduce or eliminate the limitations of attention, or, correspondingly, that perceptual learning depends on the attention condition. Object attention is a robust limit on performance. Two attributes of a single attended object may be reported without loss, while the same two attributes of different objects can exhibit a substantial dual-report deficit due to the sharing of attention between objects. The current experiments document that this fundamental dual-object report deficit can be reduced, or eliminated, through perceptual learning that is partially specific to retinal location. This suggests that alternative routes established by practice may reduce the competition between objects for processing resources.

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1. Introduction

Visual perceptual learning is widely seen as tightly coupled with visual spatial or feature attention (Ahissar & Hochstein, 1993, 2004; Crist, Li, & Gilbert, 2001; Dolan et al., 1997; Gilbert, Sigman, & Crist, 2001; Goldstone, 1998). It is postulated that attention may focus the learning process on relevant sensory representations or provide the task context that mediates performance and also that attention may be necessary for learning and consolidation. In only a few surprising cases has perceptual learning been decoupled from task attention in cases of learning of subliminal tasks in the presence of a primary, attended task (Seitz & Watanabe, 2008; Watanabe, Náñez, & Sasaki, 2001). These discussions focus on the role of attention in perceptual learning. A directly coupled but obverse question is how perceptual learning may differentially affect attention.

The literature has a number of different ideas about how attention potentiates perceptual learning. So, for example:

> *"Learning is therefore attention driven, where attention is the mechanism for choosing the relevant neuronal population, by increasing its functional weight."* (Ahissar & Hochstein, 2004, p. 460).
>
> *"... perceptual learning involves direct interactions between areas involved in face [and object] recognition and those involve in spatial attention, feature binding, and memory recall."* (Dolan et al., 1997, p. 596).
>
> *"Perceptual learning shows strong interaction with attention, indicating that it is under top–down control. Attention is necessary for consolidation...,"* (Gilbert et al., 2001, p. 684).

These quotes illustrate the strong theoretical coupling of perceptual learning and attention in current thought. They also illustrate the variety in interpretations of the role of attention in perceptual learning. The distinct emphases may follow the differences in perceptual learning tasks being considered. But they also reflect the fact that the role of attention is inferred from general beliefs or from association of observed physiological changes during perceptual tasks throughout learning and those observed in attention. Few perceptual learning reports explicitly manipulate attention to determine the interactions of perceptual learning and attention (but see Watanabe et al., 2001, for an unusual case in which perceptual learning is documented for unattended stimuli that correlate with attended task stimuli).

In this paper, we invert these claims that perceptual learning relies on attention and examine the consequences of perceptual learning for a task that explicitly manipulates attention. The inverse claim that perceptual learning alters the role of attention is related to early reports of developing target automaticity (Shiffrin & Schneider, 1977; Schneider & Shiffrin, 1977; see also Joseph, Chun, & Nakayama, 1998). Here, the interaction between perceptual learning and object attention is examined by comparing same-object versus dual-object attention conditions through the

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course of perceptual practice. The two approaches are, however, two different perspectives on the same data: if perceptual learning reduces the differences between attention conditions then by definition perceptual learning changes performance more in one attention condition than in another.

1.1. Evidence for interactions of attention and perceptual learning

What is the basis of the strong claims for the mediating role of attention in perceptual learning? Crist et al. (2001) argued that perceptual learning was under top–down control. Their study examined perceptual learning of a bisection task in monkey. They found substantial improvements in bisection performance, while the basic receptive field properties of early sensory neurons were essentially unaffected by perceptual training. However, responses to extra-task visual elements were altered depending on performance of the visual task, and so they inferred, in part, that perceptual learning was mediated by attention, or that attention engaged the changes in processing from learning. However, perceptual learning and attention were not jointly manipulated. Our interpretation is that the reported changes in response to irrelevant visual elements reflected engagement of spatial attention during task performance to task-relevant visual elements, and may or may not have been associated with perceptual learning.

Ahissar and Hochstein (2004) invoke a central role for attention in perceptual learning in their review of the differences in speed of perceptual learning for tasks of different difficulty.[1] They argue that easy tasks are learned at a high level of visual representation, while more difficult tasks must invoke changes at the early sensory levels, through a process of reverse hierarchical learning. The inference is that attention is critical in isolating the relevant level for learning in reverse hierarchical learning. Attention is however not manipulated in the reviewed studies.

Dolan et al. (1997) used fMRI to evaluate brain activity for degraded pictures of faces or objects either before or after perceptual learning invoked by viewing the corresponding clear pictures. In addition to differential activation in the inferior temporal regions involved in face and object recognition, they observed differential activity in medial and lateral parietal regions implicated in attention; this is the basis of their conclusion that perceptual learning involves direct interactions between face and object recognition areas and attention areas.

Goldstone (1998), in his review of perceptual learning, proposes four mechanisms of perceptual learning. One of these is perceptual learning through attention weighting, in which more attention is paid to important perceptual features or dimensions and/or less attention is paid to irrelevant ones. Goldstone cites explicit models of categorization in which the effect of learning may be to "stretch" specific perceptual dimensions (Nosofsky, 1986), but he notes that such mechanisms may reflect strategies as much as perceptual processes. In a similar vein, Ahissar and Hochstein (1993) trained the detection of a local texture patch, or trained the identification of the long side of the overall element display; they argued that the substantial independence of these two tasks implied a role for attention in selecting which aspects of the stimulus are trained; however this can alternatively be interpreted as training distinct tasks rather than as an interaction of attention and perceptual learning.

So, these claims that attention is critical in mediating perceptual learning are based on theoretical inferences about the processes involved in specific tasks. In none of these studies was perceptual learning explicitly examined jointly with an attention manipulation. Indeed, the most direct precursors to the current studies may be the seminal studies of automaticity in attention of Shiffrin and Schneider (1977).

In summary, there is an increasingly held view that perceptual learning and attention are fundamentally intertwined. There are two complementary forms that this proposition might take:

(1) *That attention improves, and perhaps is necessary for, perceptual learning*. This implies that perceptual learning should be faster when the stimulus and/or task is attended, and that perceptual learning may be slowed, or perhaps even impossible, in the absence of attention.
(2) *That perceptual learning may reduce, and ultimately overcome, performance limitations due to attention*. In this view, performance is naturally reduced in an unattended or divided attention condition, and perceptual learning may serve to overcome these attention limitations.

As this brief review of the literature illustrates, there is in fact little direct evidence to either support or challenge either proposition. The current paper seeks to address these issues by examining the interaction between perceptual learning and object attention.

1.2. Object attention

Dual-object report deficits – performance decrements in reporting two features of different objects compared to reporting two features of a single object – have been documented in human observers for many pairs of features, including brightness and orientation (Duncan, 1984), displacement and orientation (Duncan, 1993a), "where" and "what" (Duncan, 1993b), surface properties such as color, brightness, texture, and boundary properties such as length and location (Duncan & Nimmo-Smith, 1996). Object attention effects have been used as a method of validating object segmentation properties in visual perception (Davis, Driver, Pavani, & Shepherd, 2000). Competition between objects for visual processing resources (Behrmann, Zemel, & Mozer, 1998, and other models) has evolved as an organizing principle in understanding cortical mechanisms of visual attention (e.g., Desimone, 1998; Kastner & Ungerleider, 2000).

In an extension (Han, Dosher, & Lu, 2003), object attention limitations were tested on dual-object dual reporting of dimensions (orientation and phase) of basic objects (sine patches) that correspond with the features of early visual analysis. These experiments, as expected, documented a substantial object attention effect, but only in cases where distinct features were reported in the two objects (phase for one and orientation for the other). Surprisingly, Han et al. (2003) found that the dual-object report deficits were limited to those cases where distinct features were reported for the two objects; when the two object reports were compatible (both phases or both orientations), the dual-object deficit was reduced or eliminated – a point supported in a careful review of the prior literature, despite some claims to the contrary. The experiments in this paper are directly based on these prior experiments of Han et al. (2003) that focus on object attention, where objects occur here in separate spatial location. It does not address feature attention.

1.3. Experimental overview

In this paper, we report a case in which perceptual learning is explicitly measured in the presence of a manipulation of object attention. The fundamental object-based limitations in multiple attribute report are reduced, and possibly almost eliminated with extended practice, through perceptual learning. Data are reported from two experiments involving the same basic perceptual dis-

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[1] We (Jeter, Dosher, Petrov, & Lu, 2009) have argued that these differences in learning are controlled not by task difficulty, but by task precision.

crimination task comparing dual-object to same-object attention for the identification of orientation and phase in simple Gabor stimuli.

2. Experiment 1

This experiment examines the effects of perceptual learning through practice on individual or dual judgments of orientation and/or phase of one or two Gabor objects. Two objects appeared separately across the fixation point on each test trial (Fig. 1a). The two objects were briefly presented Gabor patterns that varied in orientation (top tilted right or left by 8 deg from vertical) and in phase (center bright versus center dark), attributes coded in early visual system (Graham, 1989).

In different blocks of trials, observers were instructed to report a *single attribute of a single object* (1O1R – 1 object 1 response, either orientation or phase in separate blocks of trials for the object indicated by an arrow pre-cue), *two attributes of a single object* (1O2R – either orientation first or phase first in separate blocks for the object indicated by an arrow pre-cue), or *two attributes from two objects* (2O2R – 2 objects 2 responses, either phase on the left and orientation on the right or vice versa in separate blocks of trials in the order indicated by an arrow pre-cue). These are conditions known to engender a large dual-object report deficit in which dual-object reports (2O2R) are less accurate than corresponding single-object controls (1O2R or 1O1R) (Duncan, 1984; Han et al., 2003). Each of the three attention/report conditions was tested in separate blocks of trials, within the same day.

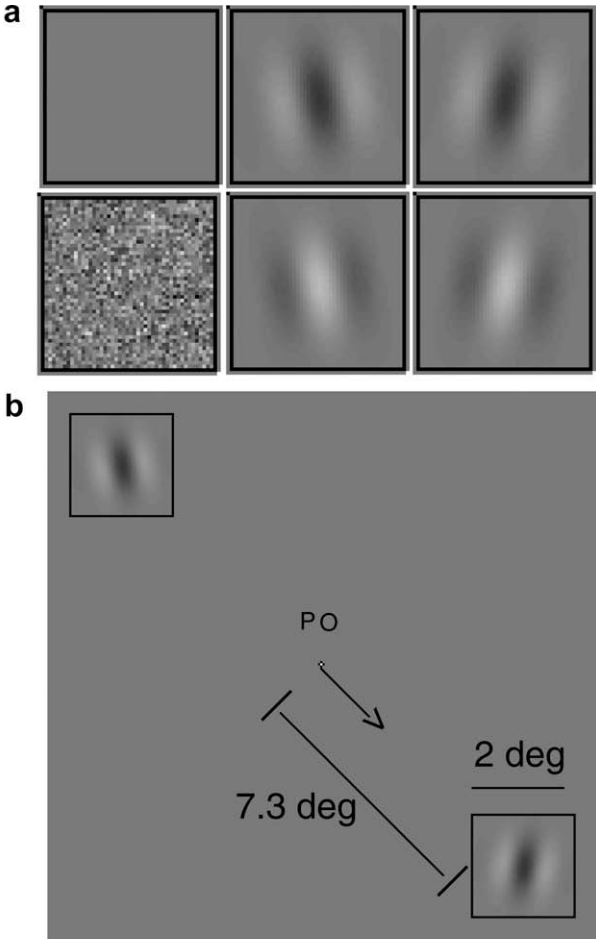

Fig. 1. Experimental stimuli and layout. (a) Individual stimuli, including sample no-noise and high noise pre- and post-fields, and four signal Gabor patches: center black tilted right, center black tilted left, center white tilted right, center white tilted left. (b) Layout of a stimulus frame including the signal Gabor patches. The left and right patches were chosen independently from the four possible signal stimuli shown in (a).

Observers practiced in a zero noise condition and in a high external noise condition, randomly intermixed within blocks, to evaluate the improvements in two possibly distinct mechanisms of perceptual learning and attention (Dosher & Lu, 1998, 1999, 2000a, 2000b; Lu & Dosher, 1998, 2008). Improvements in no external noise are attributed to stimulus enhancement while improvements in high external noise reflect external noise exclusion.

Perceptual learning often is specific to the particular trained task, stimulus, or location. This specificity, or failure of full transfer, is a characteristic aspect of perceptual learning (Ball & Sekuler, 1982, 1987; Crist, Kapadia, Westheimer, & Gilbert, 1997; Fiorentini & Berardi, 1980, 1981). Experiment 1 incorporates a specificity test by examining task performance after a switch to a new spatial diagonal of test positions following training on the original diagonal.

2.1. Methods

2.1.1. Displays

Two objects – Gabor (windowed sine wave) patterns with square frames – were characterized by two attributes, orientation (top tilted clockwise or counterclockwise of vertical by 8 deg) and phase (center dark or center light) (Fig. 1a). The two objects appeared in a diagonal layout (Fig. 1b), either in the upper left and lower right quadrants or in the upper right and lower left quadrants. These diagonal layouts were used to equate pre-and post-transfer conditions for possible perceptual differences in the upper and lower hemi-field. The 2 deg × 2 deg test patches appeared on each trial at 7.3 deg from fixation, at a viewing distance of 70 cm. The Gabor patterns are described by:

$$l(x,y) = l_0\left(1.0 \pm c\cos\left(2\pi f(x\cos(\pm\theta) + y\sin(\pm\theta))\right) \times \exp\left(-\frac{x^2+y^2}{2\sigma^2}\right)\right)$$

The orientation, θ, of the pattern, was ±8° from vertical; f, the spatial frequency of the pattern, was 1/24 pixels (1 *cpd*) and , the standard deviation of the spatial window, was 9 pixels (0.37 deg). The value l_0, is the neutral (background) luminance, and c is the maximal contrast of the pattern. The values of θ and σ were chosen from pretesting to approximately equate the difficulty of the orientation and phase judgments at a given contrast. In this experiment, two contrast levels were used. The signal contrast levels for no external noise conditions were 0.055 and 0.075 and the signal contrast levels for high external noise conditions were 0.4 and 0.55, where 1.0 is the maximum contrast of the monitor. These values were selected to yield quite distinct response accuracies, and to be approximately equated in percent correct with and without external noise.

External noise images (Fig. 1a) were added to the signal pattern on half of the trials. Noise images were composed of 2 × 2 pixel (0.083 × 0.083 deg^2) noise elements. Contrasts of the noise elements were Gaussian distributed with mean 0 and standard deviation of 0.33. Noise images preceded and followed the signal image, combined with temporal integration in the visual system; noise or signal images appeared every 33 ms.

2.1.2. Apparatus

Signal and noise frames were displayed by a Power Macintosh 7300 on a Nanao Technology monitor with a P4 phosphor and a refresh rate of 120 Hz. A special circuit produced 6144 distinct gray levels (12.6 bits), and lookup tables divided the entire dynamic range ($1\ \mathrm{cd/m^2}$–$140\ \mathrm{cd/m^2}$, l_0, = $70\ \mathrm{cd/m^2}$) linearly into 256 luminance levels. The monitor was linearized using a psychophysical procedure and checked with photometric measurements.

2.1.3. Design and procedure

Two observers initially trained with an upper left/lower right layout and switched to a lower left/upper right layout, while two other observers were tested in the opposite order. Within condition, performance was tracked over 12 sessions of practice, one per day, in a given layout, and then switched to the other layout.

The distinct report conditions were carried out in separate blocks of trials. In single-object single-response (1O1R) blocks, either the phase or the orientation of the Gabor indicated by an arrow appearing 118 ms prior to the signal stimulus was reported. In single-object dual-response (1O2R) blocks, both phase and orientation (in counterbalanced order) were reported for the precued Gabor. In the dual-object dual-response (2O2R) blocks, the phase of one object and the orientation of the other was reported, phase on the left and orientation on the right (or vice versa, counterbalanced), with the order of report indicated by the pre-cue. Each experimental session, which included one pass (sub-sessions) through all of the conditions, yielded 60 trials for each combination of task condition, external noise level, and contrast level for single-object single-response, single-object dual-response and the dual-object different-response conditions.

Each observer practiced on an original layout for 12 sessions on 12 days. After this, the observer was switched to the alternative layout, and practiced for an additional six sessions on different days. A block cue (e.g., OP for orientation on the left object and phase on the right object) began each new block. The display sequence in a trial showed a fixation display (two-letter instruction, central fixation, and outline squares) for 333 ms, followed by a pre-cue arrow pointing at one object for 118 ms, followed by the stimulus consisting of a noise (or blank) display, a signal display, a noise (or blank) display (33 ms each), and a post-stimulus cue display identical to the pre-cue (until the first response). Observers responded to the stimulus on the left with their left hand ("d" or "f" for either top left or right, respectively for orientation judgments or for center black or white, respectively for phase judgments) and to the stimulus on the right with their right hand ("j" or "k", correspondingly).

2.1.4. Observers

Four observers participated in this experiment and were paid for their services. The observers had normal or corrected to normal vision. Observers participated in 20 experimental sessions.

2.1.5. Analysis

The quality of performance over sessions of practice was indexed by 2-alternative forced choice percent correct (baseline = 50%) averaged over contrast levels; the pattern of results also holds for each contrast separately. Object effects were estimated as the percent correct for the 2O2R conditions minus the percent correct for the corresponding 1O2R conditions (PC(2O2R)–PC(1O2R). These differences were tested via z-test for individual observers; significance tests over observers are combined with Friedman $\chi^2 = -2\sum_{i=1}^{k} \ln p_i$, where p_i is the p-value for k individual observer tests with df = $2k$. Regression analyses were calculated on object effect scores using a Matlab subroutine. Joint regressions (with common slopes for sessions 1–12 (or 13–18) for all conditions, but independent intercepts for each condition) were compared with fully independent regressions using a χ^2 test for nested models: $\chi^2 = n\ln(RSS_{reduced}/RSS_{full})$, with degrees of freedom equal to the difference in the number of predictors. The joint regressions are shown for these data.

2.2. Results

Perceptual learning is measured in this experiment by the improvement with practice in percent correct identification of orientation or phase for stimuli of fixed contrasts. Fig. 2 graphs the percent correct data averaged over observers and contrast conditions; these data patterns are representative of those for individual observers and the two contrasts separately. The results are shown for orientation judgments (top) and phase judgments (bottom) for no external noise (left) and high external noise (right). The approximate equivalence of the initial accuracy of the single-report conditions for the two noise conditions was contrived by choosing much lower signal contrasts for no external noise than for high external noise. Each point is the accuracy of response for a given session (day) of practice. The test position layout is swapped between the 12th and 13th sessions, indicated by the vertical dashed line.

As expected from object attention theory and the results of Han et al. (2003), there was a clear dual-object report deficit – the dual-object dual-report (2O2R) condition (squares) performance accuracy was reduced compared with either of the single-object single-report (1O1R) (diamonds) or single-object dual-report (circles) controls, especially early in training of each task layout. The performance on each of the two single-object conditions is similar, though perhaps the 1O1R condition tends to yield a slightly higher performance. In this case, the dual-object report deficit occurred in both zero external noise and in high external noise. These patterns are replicated independently in almost every session (see 95% confidence interval error bars in Fig. 2).

Perceptual learning occurred for all conditions. The performance accuracy during the last two blocks of the first phase of training systematically exceeded the accuracy of the first two blocks (z-tests for the average data for all 24 comparisons of 2 phase/orientation × 3 judgment conditions × 2 external noise × 2 contrast conditions, all $p < .01$; 24 combined individual χ^2 tests, all $p < .01$). With respect to claims that perceptual learning is mediated by focal attention, it is interesting to note that the rate of perceptual learning appears to be similar for the simple focal attention (1O1R) condition as for the most challenging dual-object (2O2R) condition, where attention must be spread across objects and report tasks. Indeed, the diffuse attention condition (2O2R) seems to show faster learning (see regression analysis below).

Additionally, there was a consistent reduction in performance at the point of the switch of task layouts (i.e., from objects in the lower-left and upper right major diagonal to those in the upper-left and lower-right minor diagonal, or vice versa). The performance accuracy during the last two blocks of the first phase of training systematically exceeded the accuracy of the first two blocks of the transfer condition (z-tests for the average data for all 24 comparisons of 2 phase/orientation × 3 judgment conditions × 2 external noise × 2 contrast conditions, 16 of 24 $p < .01$ and 6 of 24 $p < .05$; 24 combined individual χ^2 tests, 14 of 24 $p < .01$ and 5 of 24 $p < .05$).

For each of the phase and orientation and no and high noise conditions, we computed a specificity index, $S = 1 - (pc_{1sttransferpoint} - pc_{1sttrainingpoint})/(pc_{finaltrainingpoint} - pc_{1sttrainingpoint})$, which is 1.0 when the initial performance at the transfer equals the initial performance in the training and will be 0 if the transfer takes up where the training left off. These specificity scores averaged about 0.5, with the average over orientation and phase and noises of 0.48 for 1O1R, 0.45 for 1O2R, and 0.50 for 2O2R conditions (range 0.21–0.70 for individual condition scores). These indices, then, suggest that this task shows about 50% specificity, and that this specificity is essentially the same for the three different object attention conditions.

This reduction in performance with a switch in layout indicates that perceptual learning in this task was partially specific to retinal

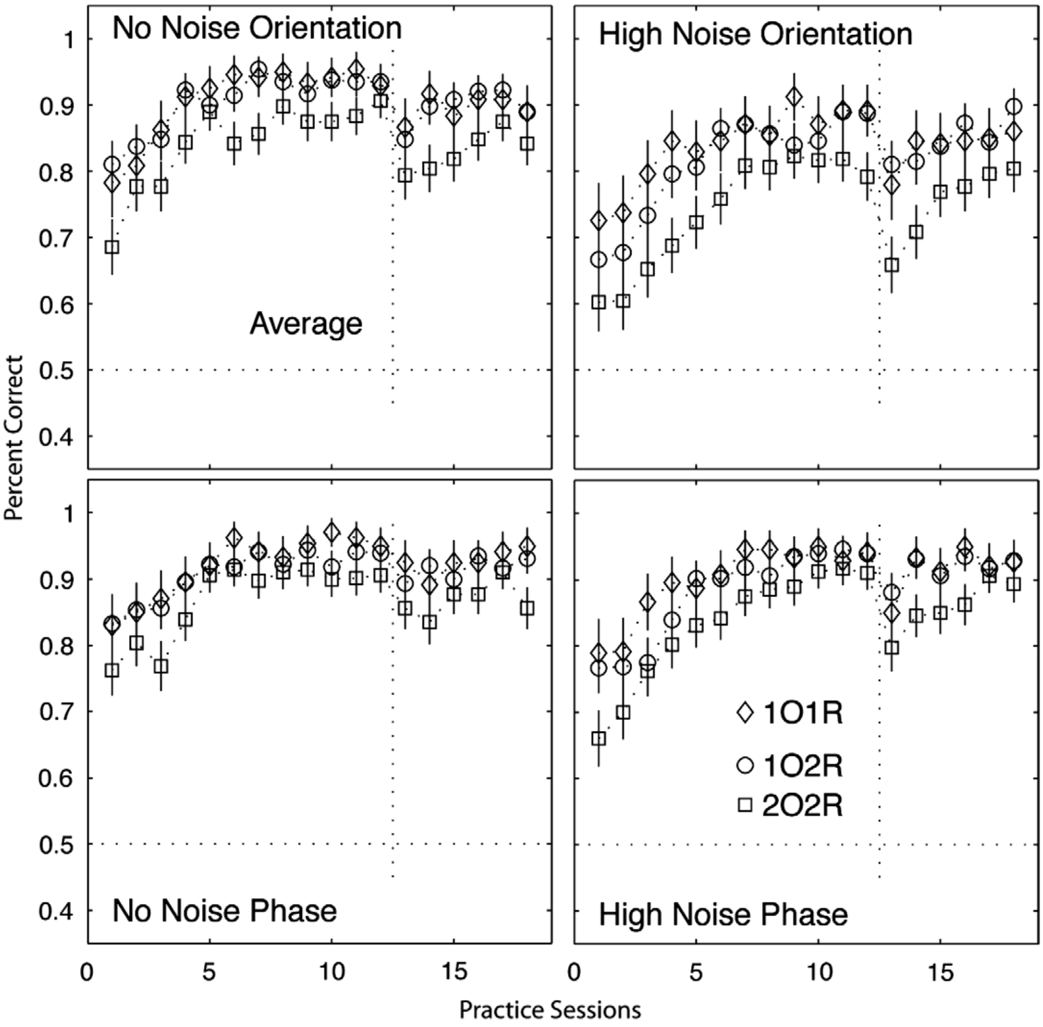

Fig. 2. Percent correct, averaged over contrasts, as a function of practice for single-object single-response (1O1R, ◇), single-object two response (1O2R, ○), and dual-object two response (2O2R, □) for four noise and response conditions: (upper left) no noise, orientation judgments; (upper right) high noise, orientation judgments; (lower left) no noise, phase judgments, (lower right) high noise, phase judgments. The vertical dashed line indicates the switch of layout after session 12. Error bars indicate the 95% confidence intervals.

location similar to previous cases of reported specificity of perceptual learning to retinal location (e.g., Karni & Sagi, 1991; for reviews, see Ahissar, Laiwand, Kozminsky, & Hochstein, 1998; Karni & Bertini, 1997). Such specificity has been associated by many with plasticity at early levels of visual system (V1/V2), but that may also be consistent with reweighting from stable and unchanged perceptual representations at the early visual levels to a task decision (Dosher & Lu, 1998, 1999, 2009; Petrov, Dosher, & Lu, 2005, 2006). See the general discussion for additional comments.

Importantly, the dual-object attention effect appears reduced through practice. Fig. 3 shows the object attention effect, here defined as the difference between the two probabilities correct or the dual-object report disadvantage, PC(2O2R)–PC(1O2R). This effect, evident early in practice ($p < .01$ for each observer), was reduced with practice. The reductions in the dual object effect are seen in the regression lines in Fig. 3 ($p < .001$). Regressions were first run on the four panels of pre-switch data. The slopes of improvement did not differ significantly in the four panels, indicating approximately the same rate of learning in no and high external noise and for the orientation and phase judgments. Fitting with a common slope, the resulting regressions estimated the slope as 0.0037/block ($r^2 = .3702$, $F(5, 43) = 6.318$, $p < 0.0004$, $serr = 0.0006$; 95% confidence interval on the slope of [0.0016–0.0058]). Next, regressions were run on the post-switch data, which also could be fit with the same slope; fitting with the same slope, the post-switch regressions estimated the slope as 0.0078/block ($r^2 = .46$, $F(5, 19) = 4.086$, $p < 0.015$, $serr = 0.0007$; 95% confidence interval on the slope of [0.0011–0.0144]).

At the beginning of practice, the object effect, or deficit, was 9%, averaging over noise and judgment conditions. After 12 sessions of practice, the average object effect was 4%. At that point, the object attention effect was not significantly different from zero for many conditions (see 95% confidence error bars in Fig. 3). The switch of layout re-invigorated the object attention effect, which was again reduced with subsequent practice ($p < .01$).

2.3. Discussion

Successful perceptual learning is widely seen as interconnected with and mediated by attention processing; perceptual learning is thought to be poor in the absence of attention. This experiment is among the first to directly investigate the effect of perceptual learning and its interaction with the effects of object attention.

One question was whether the attention condition impacted the effectiveness of perceptual learning, favoring the focal attention

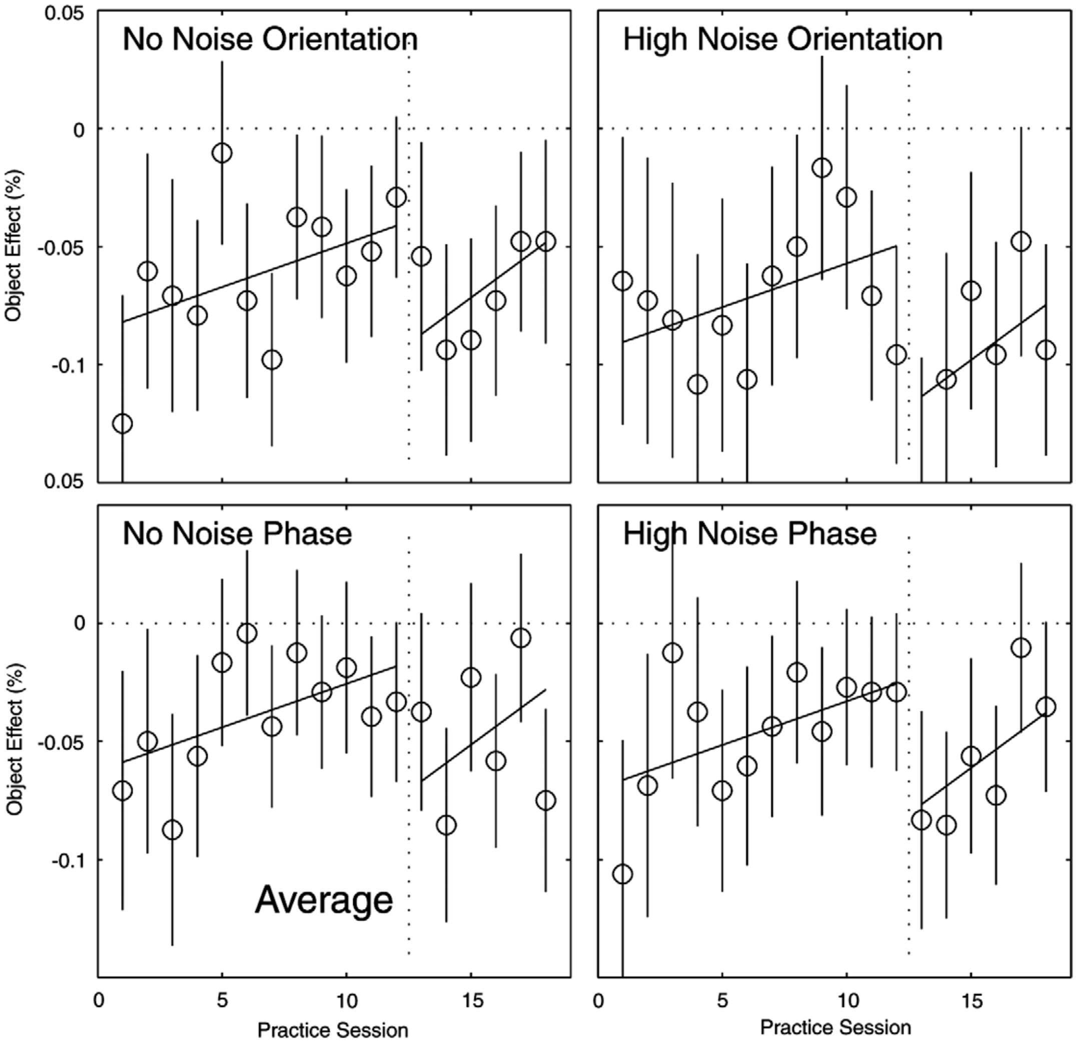

Fig. 3. The object effect (%) – dual-object report deficit (2O2R–1O2R) – as a function of practice sessions: (upper left) no noise, orientation judgments, (upper right) high noise, orientation judgments, (lower left) no noise, phase judgments, (lower right) high noise, phase judgments. The vertical dashed line indicates the switch of layout after session 12. Regression lines indicate the reduction in the object effect over sessions, separately for the two layouts.

condition. Perceptual learning resulted in overall improvements in performance accuracy in all attention conditions. As is often observed for perceptual learning, these improvements were partially specific to the test layout or retinal positions (Karni & Sagi, 1991). Perceptual learning seems to systematically reduce the size of the object attention deficit, and this too was partially reset by a switch of layout. There was, however, little evidence for faster improvements in the focal attention condition. If anything, perceptual learning in the divided attention condition appeared to be faster and of greater magnitude.

The second form that the interaction of perceptual learning and attention might take was for perceptual learning to reduce or mitigate the effect of attention. These results indeed suggest an interaction of perceptual learning and the function of divided attention. Perceptual learning may serve to support processing so as to circumvent the attention limitations associated with the processing of multiple objects. This phenomenon is distinct from that observed in previous cases where practice on a specific target in visual search lead to automatic and obligatory pop-out, and other related phenomena of visual search (Shiffrin & Schneider, 1977). Both, however, are examples of learning altering the ground conditions under which attention limitations operate. From the other perspective, the same data imply that perceptual learning apparently improves the single-object attention conditions by less than the dual-object conditions, and that the improvement of the dual-object conditions appears to persist over longer extents of practice.

The current study suggests that practice may reduce attention limitations. Could these object attention effects be (nearly) eliminated with more extensive practice? The next study reports the results of a related study that incorporated very high levels of observer practice.

3. Experiment 2

This experiment considers the data from two observers participating in an object attention experiment (Han et al., 2003) who continued practice in the task. The reduction or elimination of dual-object deficits is demonstrated especially clearly with these highly practiced observers.

The Han et al. (2003) study measured contrast psychometric functions for the three report conditions in Experiment 1, plus an additional dual-object report condition, a dual-object same-response condition in which either the phases or the orientations were reported for both objects. Han et al. (2003) found that dual-object report deficits were focused on cases where distinct responses were reported for two objects (phase for one object, and orientation for the other). The experimental task was otherwise very similar to Experiment 1.

This design (Han et al., 2003) required a much larger sample size to measure, so practice effects were evaluated by separately analyzing performance in 8–10 session (6000–9000 trial) sets of data. We also performed a fine-grained analysis of individual sessions by pooling over the three middle contrasts and averaging over observers.

3.1. Methods

3.1.1. Displays

The stimulus displays in Experiment 2 were essentially identical to those of Experiment 1. They differed in the layout, in which the two objects appeared along the vertical meridian to the left and right of the fixation point, still at 7.3 deg from fixation as before. It also differed in requiring the identification with a smaller tilt of 4 deg from the vertical. External noise images were the same as in Experiment 1.

3.1.2. Apparatus

The equipment used was the same as that in Experiment 1. The dynamic range of the display was (1 cd/m^2–50 cd/m^2, l_0, = 25.5 cd/m^2).

3.1.3. Design and procedure

Four kinds of report conditions were tested in separate blocks. Three of the four conditions were the same as in Experiment 1: a single-object single-response (1O1R) condition, a single-object dual-response (1O2R) condition, and a dual-object dual different-response (2ODR) condition (equivalent to the 2O2R condition in Experiment 1 in which the orientation of one object and the phase of the other was reported). The experiment also included a dual-object dual report condition in which observers reported either the orientation of both objects or the phase of both objects, the dual-object same-report condition (2OSR).

Full psychometric functions from chance to asymptotic accuracy were measured for all conditions. Seven signal contrasts measured the psychometric functions for each report condition in two external noise conditions (no noise and high noise). Report conditions (1O1R-P, 1O1R-O, 1O2R-PO, 1O2R-OP, 2OSR-PP, 2OSR-OO, 2ODR-OP, 2ODR-PO, where O = orientation and P = phase) were blocked separately, counterbalanced for response instruction and report order. The object to be reported (single-object conditions) or reported first (dual-object conditions) was cued randomly on each trial. See Han et al. (2003) for a full description. The procedure was essentially the same as in Experiment 1.

One observer (AS) participated for almost 17,000 trials; the data were analyzed as three stages of practice (following two initial task-orientation sessions). The other observer (BJ) participated for almost 12,000 trials; the data were analyzed as two stages of practice. Sample sizes for each point of each practice stage were approximately 120 trials (single response conditions) and 240 trials (dual-response conditions). The data from the first stage of practice were previously reported in the average data of Han et al. (2003). These two observers were willing to continue to participate in the further sessions of practice that allowed the evaluation of perceptual learning.

3.1.4. Observers

Two observers with normal or corrected to normal vision participated in the experiment. They were paid for their participation. Observer AS ran 16 sessions (composed of 16 single-object sub-sessions and 32 dual-object sub-sessions, see methods) and observer BJ participated in 12 sections (12 single-object sessions and 24 dual-object sessions).

3.1.5. Analysis

As before, the quality of performance was indexed by 2-alternative forced choice percent correct (baseline = 50%) as a function of contrast and stage of practice. Percent correct as a function of stimulus contrast for each condition was described by Weibull functions, fit using nonlinear minimization tools in Matlab and a maximum likelihood criterion:

$$p_i = \min + (\max - \min)\left(1 - 2^{(c_i/\alpha)^{\beta}}\right),$$

where p_i is the correct percentage at contrast c_i, min is the guessing baseline, max is the asymptotic maximum percent correct, α controls the location and β controls the slope of the psychometric function. Statistical tests for equivalence likelihood χ^2 tests for nested models tested whether the 2O2R and 1O2R conditions could be described with the same Weibull function (Borowiak, 1989).

3.2. Results

The percent correct for each of the four report conditions as a function of contrast is shown separately for zero external noise (left) and high external noise (right) conditions, for orientation (top panels) and phase judgments (bottom panels), and for distinct stages of practice in the task (top, middle, and bottom within each set). These data are shown for observer BJ in Fig. 4 and for observer AS in Fig. 5. Error bars are not shown to reduce visual clutter; the binomial standard deviations range from 0.02 to 0.045 for single-object conditions and from 0.015 to 0.03 for dual-object conditions, depending upon whether the probability is near 0.9 or near 0.5.

The first stage of practice reveals the dual-object report deficits reported in Han et al. (2003). There is a dual-object report deficit specifically for the dual-object different-report (2ODR) condition. As reported in Han et al., the dual-object report deficits are larger in high external noise, and smaller or sometimes non-significant in zero external noise. In contrast, the dual-object report deficits in Experiment 1 were seen in both noise conditions; it is not clear why these results differ. The dual-object different-report (2ODR) condition (squares) yields significantly lower accuracies (right-shifted psychometric functions) relative to single-object dual-report control (1O2R) (circles). See especially the upper right panel in Stage 1 and high external noise, where the proportions correct for the 2ODR, or squares, fall clearly below other conditions. As seen in Han et al., the dual-object report deficit is smaller or non-existent – even early in practice – for dual-object same-report conditions (2OSR) (triangles). There is a slight residual benefit for the single-object single-response (1O1R) compared to the single-object dual-response (1O2R) control. These results are summarized in the fits of the Weibull functions shown as the smooth curves for each condition.

Fig. 6 presents the 75% contrast thresholds, interpolated from the best-fitting Weibull curves, for the four report conditions for orientation and phase judgments in high external noise. High external noise is the condition where dual-object report deficits are robust in early stages of practice. The thresholds are shown for the two (BJ) or three (AS) stages of practice. The more difficult dual-object different-report (brown bars) initially has the highest thresholds, which then approach those of the other three report conditions with practice. One interesting aspect of the data revealed by this threshold plot is that – at least at the grain of practice measured by the learning stages in this experiment – the dual-object different-report (2ODR) is the primary condition that continues to exhibit improvements with ongoing practice; at this grain of analysis, the other conditions show only small differences in thresholds across stages.

In order to evaluate the improvements in a finer analysis of practice (at the request of a reviewer), we performed an analysis

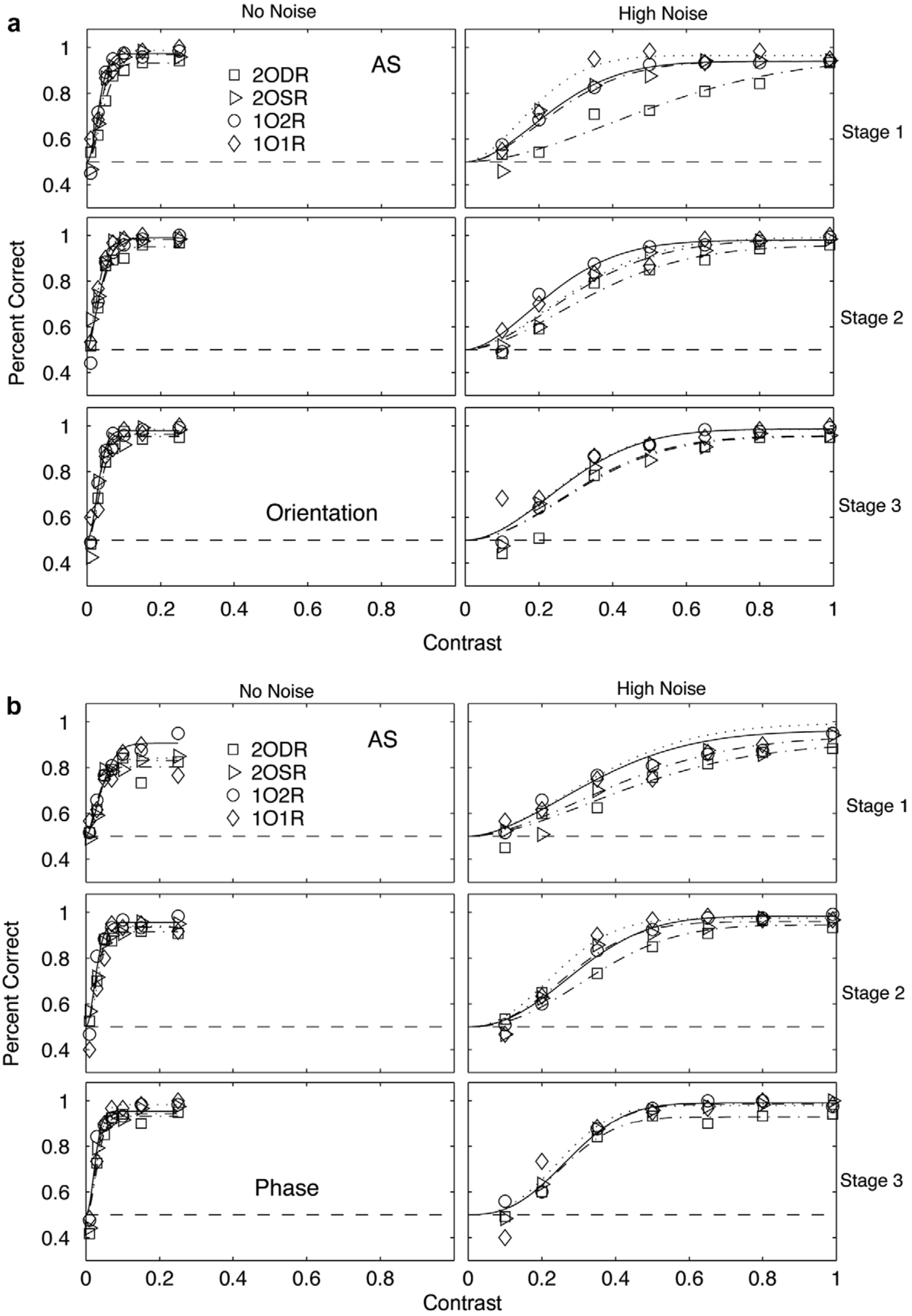

Fig. 4. Psychometric functions for four report conditions: dual-object different-report (2ODR), dual-object same-report (2OSR), single-object dual-report (1O2R), and single-object single-report (1O1R) conditions for three stages of practice (over 19,000 trials) for observer AS. The orientation judgments are in the top panels, phase judgments in the bottom panels; zero external noise (left) and high external noise (right), for three stages of practice (top, middle, lower) within each set. (Binomial error bars, omitted to reduce visual clutter, range from 0.02 to 0045 for single-object conditions and from 0.015 to 0.03 for dual-object conditions, depending upon whether the probability is near 0.9 or near 0.5.)

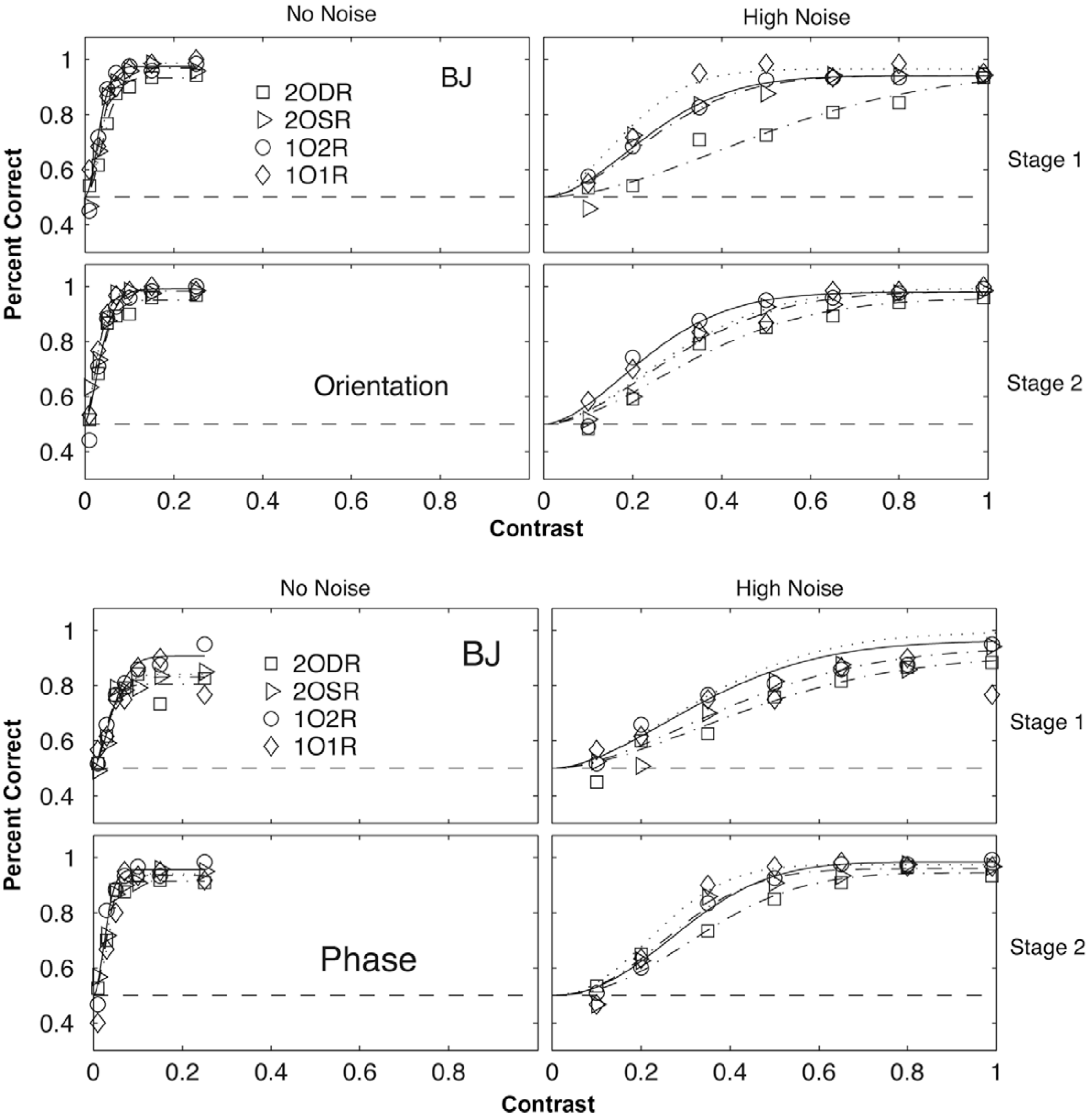

Fig. 5. Psychometric functions for four report conditions: dual-object different-report (2ODR), dual-object same-report (2OSR), single-object dual-report (1O2R), and single-object single-report (1O1R) conditions for three stages of practice (over 19,000 trials) for observer AS. The orientation judgments are in the top panels, phase judgments in the bottom panels; zero external noise (left) and high external noise (right), for two stages of practice (top, lower) within each set. (Binomial error bars, omitted to reduce visual clutter, range from 0.02 to 0045 for single-object conditions and from 0.015 to 0.03 for dual-object conditions, depending upon whether the probability is near 0.9 or near 0.5.)

of each smaller set of sections of practice. In order to accumulate a marginally acceptable sample size for each section in this experimental design, with far fewer samples per condition per session, we pooled over the middle three contrast levels and averaged over the two observers in the first 12 sessions of practice (dropping the later ones for AS). The middle three contrast levels are in the region of, but not equal to, the estimated thresholds. This provides an analysis comparable to that of Experiment 1 – although the sample sizes are lower, and the data are more variable. Fig. 7 shows percent correct for 12 sections of practice for the single-object single response (1O1R), the single-object dual-response (1O2R), the dual-object (two) different-response (2ODR, which is the same as the 2O2R in Experiment 1), and a dual-object two same response (2OSR) condition. This finer analysis reveals noticeable learning in the first two or three sessions, with some leveling off, and perhaps even reduction in the single-object conditions near the end of practice. Despite the variability in the data, the 2ODR condition generally lies below the other conditions (which are similar), especially in high external noise. This gap was reduced with increasing practice, consistent with the similar data in Experiment 1.

Fig. 8 graphs the object effect as measured in percent (2ODR–1O2R). This dual-object report deficit diminishes with practice, and the final scores are near or at an object effect of zero. As in Experiment 2 (Fig. 3), the reductions in the dual object effect are shown as the regression lines ($p < .01$). The slopes of improvement in the object attention effect were approximately the same in no and high external noise and for the orientation and phase judgments. Fitting with a common slope, the resulting regressions estimated the slope as 0.0085/section ($r^2 = .309$, $F(5, 43) = 4.809$, $p < 0.0027$, $serr = 0.0031$; 95% confidence interval on the slope of [0.0037–0.0132]).

As can be seen in both scales of analysis, the dual-object report deficit (2ODR vs. 1O2R) is essentially (and statistically) eliminated with stages of practice – there is little or no observable dual-object

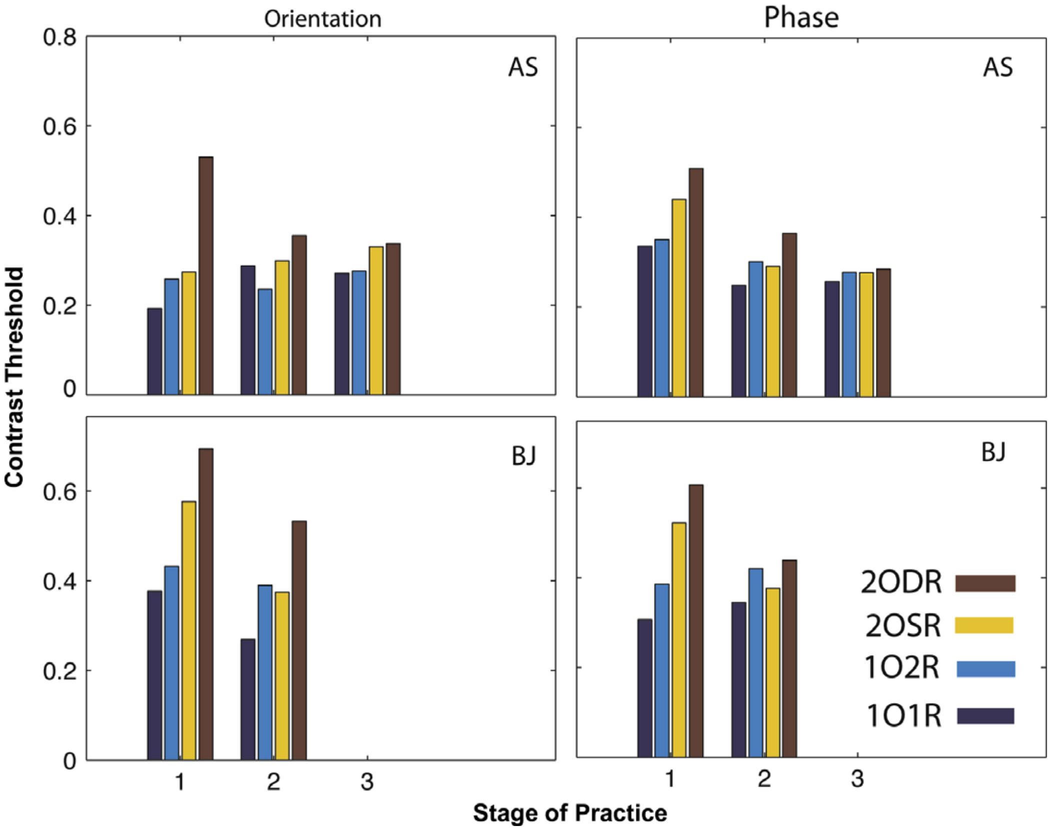

Fig. 6. Contrast thresholds for four report conditions: dual-object different-report (2ODR), dual-object same-report (2OSR), single-object dual-report (1O2R), and single-object single-report (1O1R) conditions for three stages of practice for observers AS and BJ. These thresholds are in high external noise. The higher thresholds for the dual-object different-report conditions are reduced and approach those of the other conditions with progressive stages of learning. The color codes are 2ODR (brown), 2OSR (gold), 1O2R (blue), 1O1R (black). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

report deficit in the late stage(s) of practice. These data provide an existence proof that with sufficient practice, the object effect can be eliminated.

3.3. Discussion

Experiment 2 is essentially of the same as Han et al. (2003), but continued this experiment through additional stages of practice. Unsurprisingly, the first stage of practice for each of our two observers individually replicated the average pattern in Han et al., to which they contributed. By examining the data from these two observers who participated in heroic levels of practice, it was shown that the dual-object report deficits observed early in performance are systematically reduced and nearly or completely eliminated through practice. The thresholds of the limiting dual-object different-response (2ODR) were reduced over Stages of practice to (nearly) match the thresholds of the other control conditions, such as the single-object dual-report (1O2R) condition. A finer-grained analysis showed notable improvements in all conditions over the first few sessions, with continued improvements in the dual-object different-response (2ODR) condition. Interestingly, the data imply that perceptual learning continues in the divided attention condition after performance in the focal attention conditions has stabilized.

4. General discussion

Visual perceptual learning has been widely associated with the engagement of visual attention (Ahissar & Hochstein, 1993, 2004; Crist et al., 2001; Dolan et al., 1997; Gilbert et al., 2001; Goldstone, 1998). The standard view seems to be that attending to a task is a requirement for or improves perceptual learning. As reviewed in the Introduction, the claims for an interaction of attention and perceptual learning are largely based on indirect evidence, such as an observation that brain activity during practice of visual tasks may engage the same or similar sites associated with attention manipulations (Dolan et al., 1997). Understanding the functional interaction between perceptual learning and attention will benefit from experimental investigations that directly manipulate both perceptual learning and attention. The current sets of experiments are one such example. Our presentation focuses on an inversion of the usual question to ask whether perceptual learning can modify one of the classic cases of attention limitation. However, these same data can be viewed equally from the other perspective to conclude that perceptual learning in the different attention conditions differ in a direction where the challenging attention condition benefits relatively more with practice. If anything, it appears that more learning occurs in the divided attention conditions than in the focal attention conditions.

4.1. Reducing object attention limitations

Competition for attention and neuronal resources between objects in the visual field are associated with a fundamental limitation in processing and reporting multiple attributes from different objects (Desimone, 1998; Duncan, 1984; Kastner & Ungerleider, 2000). This phenomenon has been the basis for wide-ranging investigations of the importance of object analysis and object attention in cortical processing of objects in complex visual displays. In this paper, we report a perceptual learning

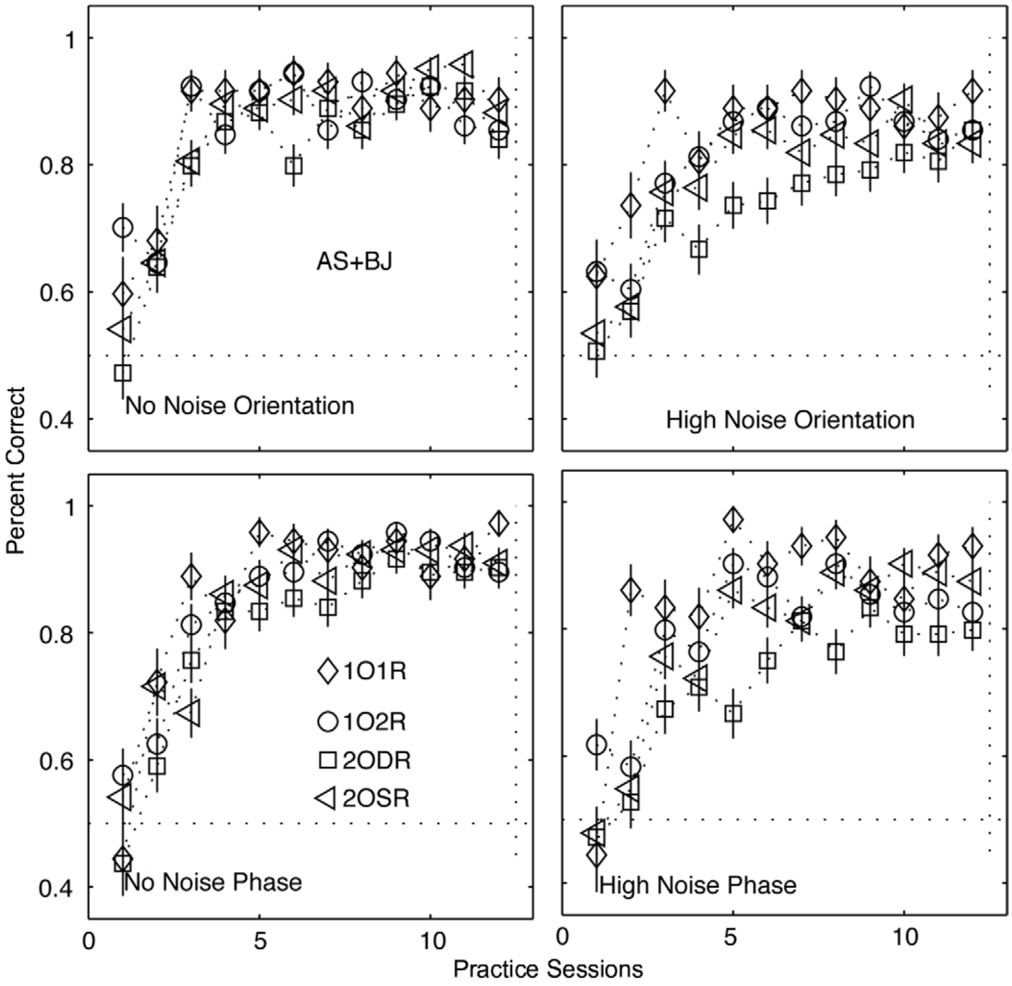

Fig. 7. Percent correct, averaged over three middle contrasts of the psychometric function and two observers (AS and BJ), as a function of practice for single-object single-response (1O1R, ◇), single-object two response (1O2R, ○), and dual-object (two) different-response (2ODR, □) and dual-object (two) same response (2OSR, ◁) for four noise and response conditions: (upper left) no noise, orientation judgments; (upper right) high noise, orientation judgments; (lower left) no noise, phase judgments, (lower right) high noise, phase judgments. Error bars indicate one standard error.

phenomenon in object attention. Perceptual learning improves the overall level of performance, but also serves to reduce the size of object attention (dual-object report deficit) effects. Indeed, with sufficient practice, the object attention effect can be essentially eliminated.

The improvements in performance and reduction of the object attention effect are both partially specific to the trained layout (objects in upper left/lower right quadrants versus lower left/upper right quadrants). Partial specificity to retinal layout, or retinal location, is viewed by many as a signature of plasticity that involve sensory representations at the level of V1/V2, where cortical representations are retinotopic and local. It is, however, also consistent with reweighting of the connections between sensory inputs at these early levels and a decision unit or at some higher level of the visual system (Dosher & Lu, 1998, 1999, 2009; Petrov et al., 2005, 2006), which is related to early claims of differential readout by Mollon and Danilova (1996). Similarly, recent results on the elimination of specificity with pretraining a transfer location with another task also might suggest learning at a higher level (Xiao et al., 2008), and this effect might interact with or depend upon attention.

With larger amounts of practice, such as that seen in Experiment 2, the limitations in dual-object reporting are gradually reduced, and ultimately nearly eliminated. These results, then, support the view that perceptual learning may develop a mode of task performance that is less dependent upon attention. This is a new observation for object attention.

These studies, then, have direct implications for the second proposition ventured earlier: *that perceptual learning may reduce, and ultimately overcome, performance limitations due to attention.* The current paper presents direct evidence in support of this proposition – in the domain of object attention.

The reductions of object attention limitations with practice relates to, but is different from, the classic case of learning in visual search (Schneider & Shiffrin, 1977; Shiffrin & Schneider, 1977). In that classic case, practice developed automaticity in identifying consistently mapped targets from distractors via a pop-out process. It seems quite possible that strengthening the response to a highly practiced target appearing in various locations in the search field is mediated by training the salience (Lu & Sperling, 1995) or priority (Schneider, 1999) of the targets. In contrast, the mechanisms involved in reductions of object attention effects in the current experiments seem unlikely to be mediated by such factors as improved salience or priority, at least in any simple way. In these object-attention experiments, the locations of the targets are known, and over the course of the experiments, all stimuli are seen and responded to exactly equally often; no one stimulus becomes more salient than any others. Similarly, in the comparisons of dual-object versus single-object report conditions, the 'targets' are the same over all conditions, and the judgments are exactly equivalent.

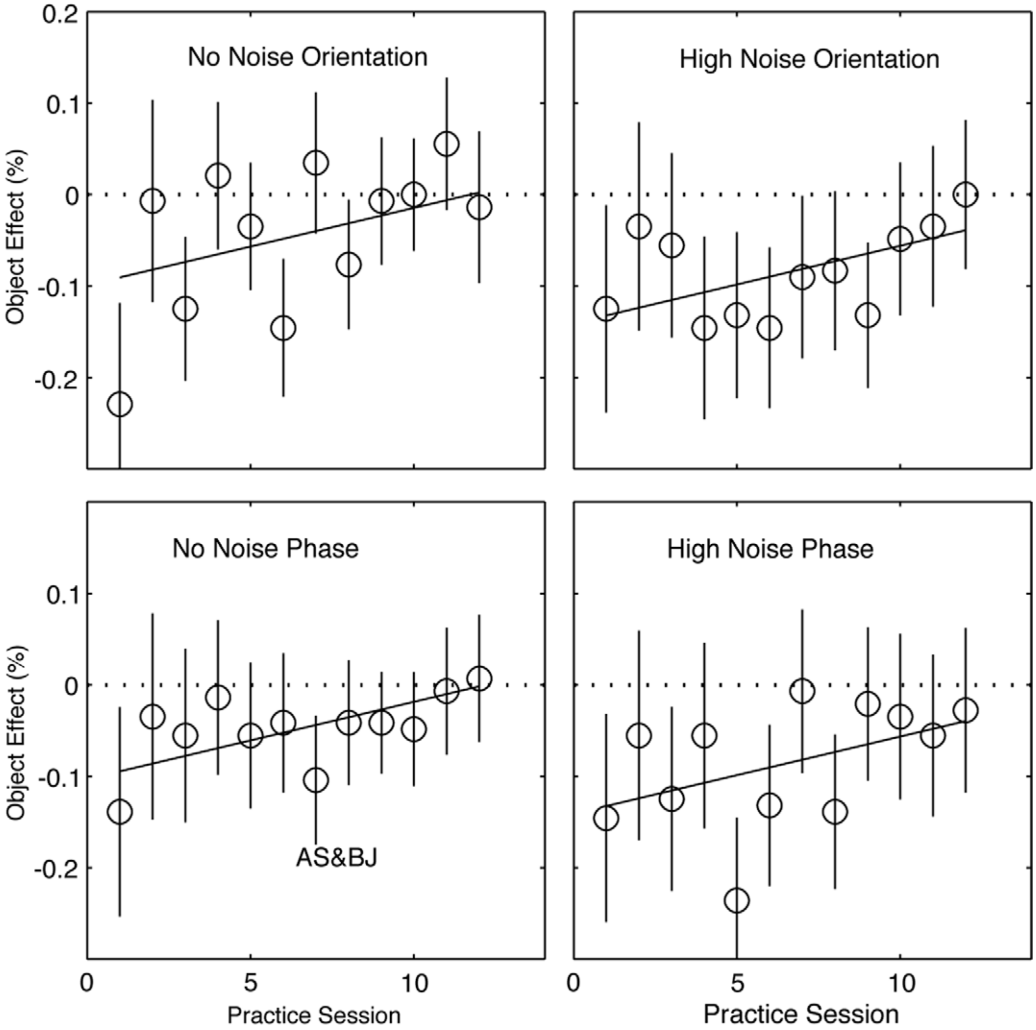

Fig. 8. The object effect (%) – dual-object report deficit (2O2R–1O2R) – as a function of practice sessions: (upper left) no noise, orientation judgments, (upper right) high noise, orientation judgments, (lower left) no noise, phase judgments, (lower right) high noise, phase judgments. Error bars indicate the 95% confidence intervals. Regression lines indicate the reduction in the object effect over sessions.

In these cases, it seems unlikely that identical models would apply to changes in visual search with practiced targets (Schneider, 1999) and those in the object attention cases. It seems more likely that dual-object conditions have developed in which the competition intrinsic to object attention is reduced (Behrmann et al., 1998).

The object attention/training phenomenon is also related to, but distinct from, claims that the conditions under which even the simplest visual detection depends upon focal attention are modified by expertise (Joseph et al., 1998). These researcher's original claim was that observers were 'blind' to pre-attentive detection of simple features (termed 'pop-out') in attention blink paradigms when their attention was diverted elsewhere; they subsequently found that more modest attention effects occur for 'expert' compared to 'novice' observers.

Our findings on the reduction of dual-object divided attention costs could benefit by extension to other forms of attention, such as feature attention. We speculate that, in general, the relative benefits for focal attention and relative challenges of divided or dispersed attention may be reduced by virtue of extended practice, or perceptual learning. In this regard, the observation of location specificity of the effects is important, as it suggests that the attention limitations are reduced through the development of alternative coded routes to performance via perceptual, rather than cognitive or motor learning. These might include the development of longer-range connections that code for object pairs. These speculations warrant additional research. Does perceptual learning always reduce or eliminate attention limitations? Or, does this phenomenon occur for some attention phenomena but not others? Does it depend upon training that optimizes perceptual learning, for example for specific stimuli, specific locations, or specific tasks?

4.2. Attention and perceptual learning

In considering the phenomenon of perceptual learning, a number of researchers have clearly associated effective perceptual learning with attention, calling perceptual learning "attention driven" (Ahissar & Hochstein, 2004) or "under top–down control" and dependent upon attention "for consolidation" (Gilbert et al., 2001). However, there are few reports in the literature that have explicitly joined an attention manipulation with perceptual learning.

The current studies also have direct implications for the first proposition: *that attention improves, and perhaps is necessary for, perceptual learning*. The current results suggest that the relationship between attention and perceptual learning may not always be so simple or direct.

The claims that attention is critical to effective perceptual learning seem to suggest faster perceptual learning with focal attention, or, conversely, limited perceptual learning without attention or with divided attention. Although the focus of these experiments was to observe the effects of perceptual learning on attention effects, still some observations about the effect of attention on perceptual learning are warranted, as exactly the same data can be viewed as differential benefit from perceptual learning for the different attention conditions. In Experiment 1, learning occurred together in both focal and divided attention conditions, yet either similar or faster learning was reported in the divided attention condition (2ODR) than in the focal learning conditions (1O1R or 1O2R) in order for the performance in the divided attention condition to "catch up" with the performance in the focal learning conditions. If focal attention were necessary for perceptual learning, or if focal attention differentially speeded perceptual learning in a simple way, then the opposite result might have been expected. (See further discussion below.)

Experiment 2 investigated a more extensive level of training and measured the full psychometric functions. Two analyses were carried out, one comparing the psychometric functions at different stages of learning (pooling over more sessions and measuring on the scale of kilo-trials), and another comparing performance in the middle three contrast conditions of the psychometric function, but estimating improvements on a more fine-grained timescale. Interestingly, here too, it is the condition most challenged by attention (2ODR) that continues to show improvements in performance, while those conditions that involve attending to only one object (1O2R) showed little or no improvements in the stage analysis, and fewer improvements after the first few sessions in the fine-grained analysis. Combining the results of both experiments suggests that the focal attention conditions achieved asymptotic performance before the divided attention condition, yet that more learning occurred in the divided attention conditions than in the focal attention conditions.

Since all of the attention report conditions are trained in the same day (although in separate blocks), these results may be consistent with initial learning in both dual-object and single-object reporting mediated through improvements in the same learned identification process. Elsewhere, we have proposed that perceptual learning dominantly occurs through modifying learned associations between the most useful sensory representations or cues and a unit for an identification decision in a specific task (Dosher & Lu, 1998, 1999, 2009; Petrov et al., 2005, 2006; see also Eckstein, Abbey, Pham, & Shimozaki, 2004). If this is so, then the same decision structures may underlie improvements in performance in each separate judgment. This would certainly be compatible with initially similar performance improvements under all attention report conditions. Yet, the dual-report conditions also require coordinating multiple responses, and so the combination also requires specific training that may go on after individual responses have been optimized.

Is perceptual learning improved by focal attention? Additional work is needed to more fully understand whether perceptual learning is more rapid, or more effectively consolidated, when practiced under focal attention conditions than when practiced under divided attention conditions. In the case of comparing single-object focal attention to dual-object divided attention, the current experiment may provide the most direct available evidence.[2] It seems likely that specific and different network models will be needed to account for distinct perceptual tasks, and different attention demands.

5. Conclusions

The current experiments study the effects of perceptual learning in distinct conditions of object attention. We conclude that perceptual learning can be instrumental in overcoming the limitations on performance due to dividing attention over two objects. The results do not strongly support the hypothesis that perceptual learning is much faster or better in single- than in dual-object conditions, but rather support a conclusion that learning in dual-object conditions continues for longer and/or with larger benefits than single-object conditions in order to allow the two to converge with practice. Perceptual learning and attention interact together in complex ways. Perceptual learning affects the limitations of attention, and attention may affect the nature of perceptual learning. The current research clearly identifies the perceptual learning-attention interface as significant, and opens the field for further investigation. A number of important questions about this interface and its role in distinct perceptual tasks remain.

Acknowledgments

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[2] A between groups comparison of single object and dual-object report conditions is unlikely to be easily interpretable due to differences in level of performance and rate of learning over individuals. However, another kind of design in which the task was identical while attention manipulations differed might be considered for some other task.

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