What is learned when learning to point at “invisible” targets?

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Binocular masking is a particularly interesting means of suppressing human visual awareness, as images rendered subjectively “invisible” via binocular masking nonetheless excite robust activity in human visual cortex. Recently, binocular masking has been leveraged to show that people can be trained to better interact with inputs that, subjectively, remain invisible. Here we ask what is learned in such circumstances. Do people become more adept at using weak encoded signals to guide hand movements, or is signal encoding enhanced, resulting in heightened objective sensitivity? To assess these possibilities, we had people train on five consecutive days, to reach toward and point at a target presented in one of three masked locations. Target intensity was set to a fraction of a detection threshold determined pretraining for each participant. We found that people became better at selecting the target location with training, even when insisting they could not see the target. More important, posttraining we found objective thresholds had improved by an amount that was commensurate with an improvement in subjective visibility. Our data therefore show that training to coordinate with subjectively invisible targets can result in enhanced encodings of binocularly masked images.

Introduction

Binocular masking is one of the most interesting means of controlling awareness of visual input. It involves the projection of different images to the same locations in each eye. If one of the two images, by design, has greater signal strength, it can reliably suppress awareness of usually salient images presented to the other eye (Arnold, Law, & Wallis, 2008; Levelt, 1968; Tsuchiya & Koch, 2005). Moreover, if steps are taken to avoid neural adaptation leading to a *change* in relative signal strength (Alais, Cass, O’Shea, & Blake, 2010), reliable perceptual dominance of the higher signal strength image (or sequence of images) can be maintained, leaving the observer unaware of the weaker masked image (see Arnold, 2011, for a more detailed explanation of binocular masking).

The development of techniques that enable persistent and reliable binocular masking (Arnold et al., 2008; Tsuchiya & Koch, 2005; Tsuchiya, Koch, Gilroy, & Blake, 2006) has facilitated a number of interesting observations regarding the efficacy of subjectively invisible inputs. For instance, while suppressed, binocularly masked images can reportedly excite a response within a range of brain regions (Fang & He, 2005; Jiang & He, 2006; Williams, Morris, McGlone, Abbott, & Mattingley, 2004), although there is some contention regarding the robustness of these observations (see Gayet, Van der Stigchel, & Paffen, 2014; Sterzer, Stein, Ludwig, Rothkirch, & Hesselmann, 2014 for reviews). Moreover, people can experience a perceptual aftereffect as a consequence of exposure to binocularly masked images (Bahrami, Carmel, Walsh, Rees, & Lavie, 2008; Fang, Murray, Kersten, & He, 2005; Maruya, Watanabe, & Watanabe, 2008), and be conditioned to have fearful responses to them (Lipp, Kempnich, Jee, & Arnold, 2014; Raio, Carmel, Carrasco, & Phelps, 2012).

A plausible factor in the efficacy of binocularly masked images is the existence of a visual pathway *not* primarily involved in generating conscious experience. It has long been argued that there is such a pathway, optimized for motor planning rather than for generating conscious experience (de Gelder & Tamietto, 2008; He, Carlson, & Chen, 2005; Milner & Goodale, 1993; Perenin & Rossetti, 1996). It is possible that activity in this pathway is less susceptible to binocular masking, allowing for a greater degree of sensitivity to masked images than is suggested by subjective experience (Fang & He, 2005; see Ludwig & Hesselmann, 2015, for a recent review). A recent study reported data consistent with this premise. Two groups of people were trained, one to reach toward and coordinate their hand

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movements with binocularly masked images, and one to verbally report on the orientation of masked images. Only the former group evidenced improved performance with training. The latter group, however, subsequently improved when they too were given reaching training (Roseboom & Arnold, 2011). These data suggest a special role for training involving motor planning when trying to develop sensitivity to binocularly masked images (for further evidence of successful motor planning in relation to subliminal inputs, see Rothkirch, Stein, Sekutowicz, & Sterzer, 2012).

If sensitivity to binocularly masked images can be taught, what, precisely, is learned? One possibility is that humans develop a heightened ability to use information that informs motor planning. This could take the form of a greater metacognitive insight into information encoding (Fleming, Dolan, & Frith, 2012; Yeung & Summerfield, 2012), with an unchanged absolute sensitivity to binocularly masked images. Alternatively, improved performance could result from improved absolute sensitivity (Ludwig, Sterzer, Kathmann, Franz, & Hesselmann, 2013). Here we will assess these two possibilities, by having people train on a task that requires them to reach toward, and attempt to point at (or poke) a target presented in one of three masked locations. This will allow us to contrast estimates of absolute sensitivity, measured using variable signal intensities before and after training, with training performance in a ballistic pointing task conducted at a fixed signal intensity. Our results should reveal if absolute sensitivity is improved by training, or if people simply become better at coordinating with masked inputs.

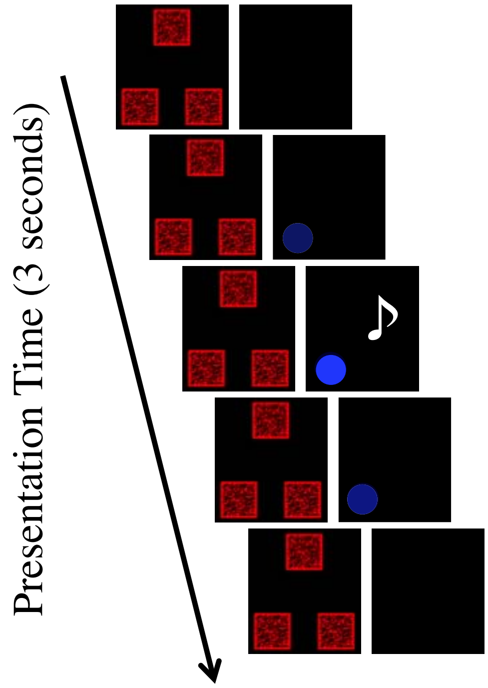

Figure 1. Graphic depicting the time course of a test presentation. Test presentations persisted for 3 s. During this time dynamic noise was presented in three locations, visible to the left eye through a red filter. A blue circular target was presented in one of the three locations, visible to the right eye through a green filter. During the 3-s presentation, target contrast was modulated (on, then off), reaching a maxima at 1.5 s. At this point a tone was sounded (signified by the music symbol), cueing the participant to try to "poke" the target.

General methods

Twelve volunteers participated. Of these, two were the authors of the study. All participants, barring the authors, provided written consent to participate in the study, as per requirements of the ethics committee at the University of Queensland, who provided approval for the study. No demographic information was recorded.

Experimental stimuli were generated using Matlab R2012b software (MathWorks, Natick, MA) in conjunction with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997), and were presented on a Dell 2714t liquid crystal touchscreen display at a resolution of 1920 × 1080 pixels updated at 60 Hz. Stimuli were viewed from 60 cm while the participant wore red/green anaglyph glasses, with the head placed in a chin rest. Responses were recorded via the touch screen.

Targets consisted of blue (CIE x 0.18, y 0.10) discs, with a diameter subtending 2 degrees of visual angle (dva) at the retina. Targets were visible to the right eye through a green filter. Masks consisted of red (Commission Internationale de l'Eclairage [CIE] x 0.66, y 0.32, Y 39.9) and black square noise patterns, subtending 2 dva in width and height with individual elements subtending 0.03 dva in width and height. These were updated at a rate of 10 Hz, to generate binocular masking via a continuous flash suppression protocol (Tsuchiya & Koch, 2005). Masks were visible to the left eye through a red filter and were surrounded by solid red frames that subtended 0.3 dva in width. Test locations were centered 6 dva directly above, or 4 dva below and 4 dva left or right of the display center (see Figure 1). There was no fixation point (participants were free to gaze about the display). During test presentations noise masks and a target were displayed on sequential monitor updates.

Preliminary and posttraining thresholds

Objective thresholds for target detection thresholds were estimated from blocks of trials completed before and after training. During these blocks of trials target location was determined at random on a trial-by-trial basis, and peak target luminance was modulated according to a method of constant stimuli. Each of 10 peak target luminance values (0.19, 0.20, 0.29, 0.39, 0.56, 0.81, 1.09, 1.49, 1.82, and 2.34) was sampled 10 times each, for a total of 100 individual trials, all completed in random order.

At the beginning of each trial, participants rested their hand on the table in front of them, below and in front of the monitor. Individual test presentations persisted for 3 s, during which target luminance was modulated according to a raised contrast Gaussian envelope—reaching a peak after 1.5 s. At this point a tone was heard, prompting the participant to indicate the target location by reaching toward and touching it. Correct responses were recorded if the participant touched the target location before the end of the test presentation (within 1.5 s of being cued to respond; see Figure 1).

After test presentations a posttest response display was presented, allowing the participant to report if they felt they had seen the target (by pressing a box labeled "Saw It!") or not (by pressing a second box labeled "Guess"). Individual target detection thresholds were estimated by fitting logistic functions to proportional correct data from each block of trials, and taking the target luminance that coincided with the 67% point on the fitted function. Note that these target detection thresholds were measured in the presence of a dynamic noise mask.

We also determined estimates of the threshold luminance for *subjective* target visibility (the luminance at which participants would report having "seen" the target), also on an individual basis, by fitting logistic functions to proportion "seen" data, and taking the 50% point on fitted functions. Finally, a subset of participants were available for retesting of objective thresholds, from 18 to 43 weeks ($M = 180$ days, $SD = 54$ days) *after* they had completed training. We retested these participants to determine if training related improvements in sensitivity to masked targets had persisted posttraining.

Training

Peak target luminance was set to 85% of the participants' target detection threshold determined in the preliminary baseline procedure. Blocks of training trials consisted of 100 individual trials, wherein the participant would attempt to reach toward and touch masked targets randomly presented in one of the three masked locations. The posttest response display again contained a button labeled "Saw It!," but also an "I-shaped" region they were required to selectively press on to indicate their level of confidence in task performance when they felt they had not seen the target. The top region was labeled "Certain," and if pressed a confidence rating of 1 was recorded. The bottom region was labeled "Guessing," and if pressed a confidence rating of 0 was recorded. Proportional confidence ratings were recorded when participants pressed positions in between these two endpoints. Feedback was provided, via an unmasked re-presentation of the target in the masked location at full intensity for 1 s, when the participants had reported that they had not seen the target, but not otherwise (see Figure 2). Each participant completed five blocks of training trials on consecutive days.

Control task

Participants also completed a control task. Details for this were as for training blocks of trials, except that only 50 trials were completed, and participants wore a patch over their left eye, so they could not see the dynamic noise mask. Performance in this control task allowed us to determine if performance had been limited by target visibility, independent of masking.

Results

Analyses of training data were restricted to trials wherein participants had reported not seeing the target. A repeated measures analysis of variance revealed a main effect of training day on proportion correct, ($F_{4,44} = 4.21$, $p = 0.006$, $\eta_p^2 = .28$; see Figure 3), with performance improving with training. Examination of performance on Control blocks revealed 2 participants whose performance on training trials was probably limited by target visibility, independent of masking, as they had failed to identify target location on more than 85% of trials when presentations were unmasked. Re-analysis of data excluding these two participants confirmed the beneficial impact of training ($F_{4,36} = 4.77$, $p = 0.003$, $\eta_p^2 = .35$).

Training had no discernable impact on levels of felt confidence, averaged across participants, on trials wherein the participant had reported *not* seeing the target ($F_{4,44} = 1.5$, $p = 0.218$, $\eta_p^2 = .12$; see Figure 4). This held true even when analysis excluded the two participants whose performance was likely limited by target visibility independent of masking ($F_{4,36} = 1.32$, $p = 0.283$, $\eta_p^2 = .13$). Nor was there a discernable impact of training on the proportion of trials wherein participants reported *seeing* the target ($F_{4,44} = 0.46$, $p = 0.766$, $\eta_p^2 = .04$; see Figure 5). Again, this held true even when we omitted the two participants, whose performance was likely limited by visibility independent of

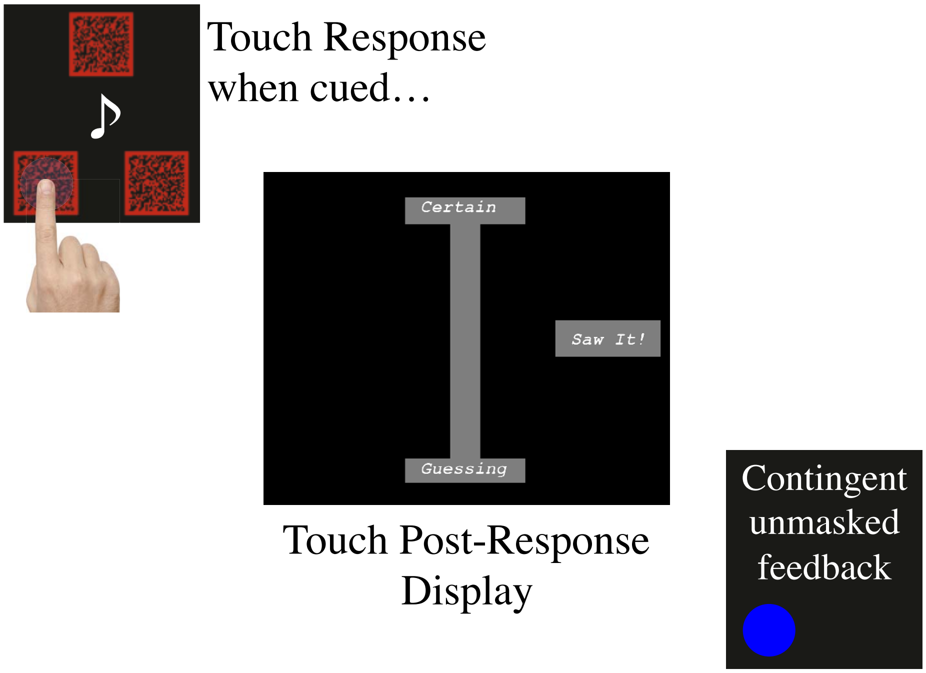

Figure 2. Graphics depicting the on-line response mode (top left), the posttest response display (middle) and contingent feedback (bottom right). Top left: Online responses were recorded via the touch display. If the participant touched the target location within 1.5 s of the tonal response cue (signified by the music symbol), a correct response was recorded. Otherwise an incorrect response was recorded. The participant could only make one online response. Middle: After each test presentation a posttest response display was presented, allowing participants to report if they had either *seen* the target or, if they felt they had not, the level of confidence they had in their online response. Bottom right: If the participants reported that they had not seen the target, the target was re-presented, at the maxima contrast without masking. If the participants reported seeing the target, feedback was not provided and data were excluded from further analysis.

masking, from analysis ($F_{4,36} = 0.45$, $p = 0.769$, $\eta_p^2 = .05$).

Individual correlations between performance and levels of confidence on trials wherein participants reported *not* having seen the target suggest some level of insight into task performance for subliminal targets. There were robust correlations between these measures, such that better performing participants were also more confident of task performance (see Figure 6a-e). Moreover, the degree of task performance improve-

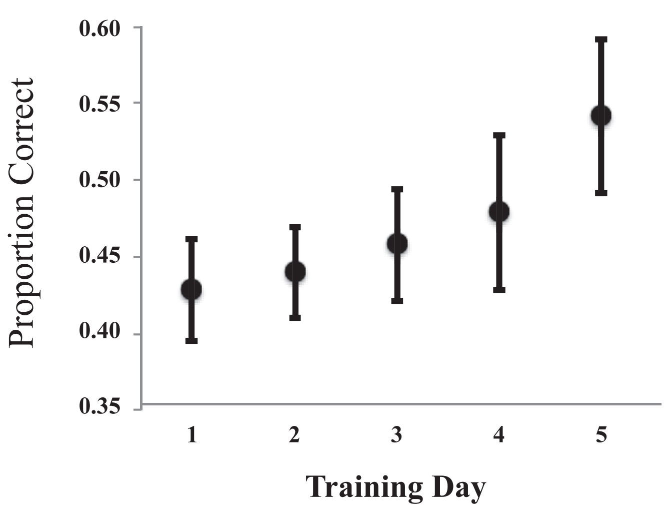

Figure 3. Proportion correct on trials wherein people reported not "seeing" the target as a function of training day. Error bars depict ± 1 *SEM*.

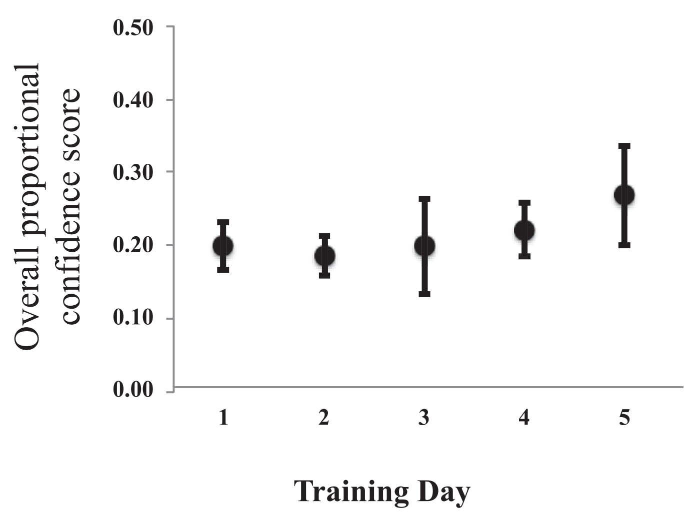

Figure 4. Overall proportional confidence scores, averaged across participants, as a function of training day. Error bars depict ± 1 *SEM*.

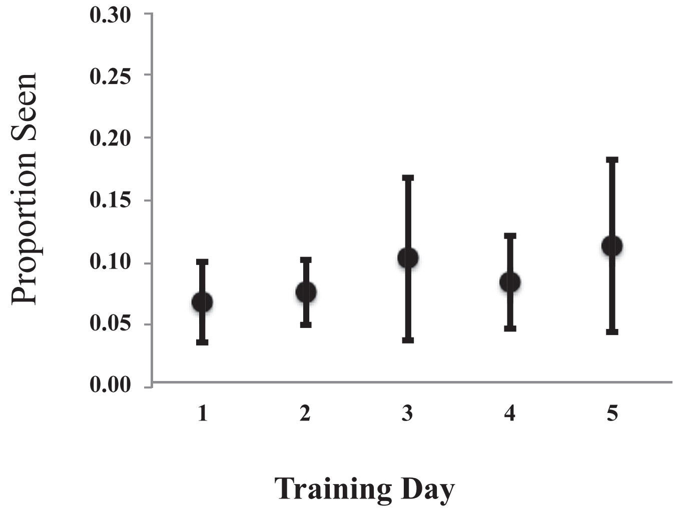

Figure 5. Proportion of trials wherein participants reported "seeing" the target, as a function of training day. Error bars depict ± 1 *SEM*.

ment, from training day 1 to training day 5, was associated with an increase in confidence (see Figure 6f).

A repeated-measures analysis of variance revealed that objective target detection thresholds had improved from pre- ($M = 0.43$ cd/m^2; $SD = 0.24$) to post- ($M = 0.32$; $SD = 0.11$) training, $F(1, 11) = 10.24$, $p = 0.008$, $\eta_p^2 = 0.48$ (see Figure 7). This analysis also revealed that subjective target visibility thresholds had improved from pre- ($M = 0.46$ cd/m^2; $SD = 0.23$) to post- ($M = 0.35$ cd/m^2; $SD = 0.15$) training, $F(1, 11) = 10.24$, $p = 0.008$, $\eta_p^2 = 0.48$ (see Figure 7). Moreover, there was no evidence for an interaction between type of threshold (objective or subjective) and training, $F(1, 11) = 0.06$, $p = 0.811$, $\eta_p^2 = 0.01$ (see Figure 7), suggesting a statistically uniform improvement in both types of threshold. There was a relationship between the degree of improvement in individual task performances and posttraining objective thresholds measured either immediately post training (see Figure 8a), or ~26 weeks later (see Figure 8b). The degree of posttraining improvement in objective detection thresholds was consistent over time (see Figure 8c).

Discussion

Our data confirm that people can be trained to better interact with subliminal visual inputs. Here people were able to "poke" binocularly masked targets with increasing success over time (improving by ~14%, from ~43% to ~57%, within a three-alternative forced choice task), despite asserting that they could not *see* the targets in question (also see Roseboom & Arnold, 2011, where people improved from chance to ~58% correct in a two-category forced choice task wherein they mimed placing their hand in between "unseen" oriented bars).

People's subjective visibility reports are evidently unreliable—in our and numerous other conceptually related studies, sensitivity was evident despite assertions of invisibility. Indeed, even on the first day of training task performance was above chance (~43% as opposed to the 33% chance level, possibly reflecting a practice effect from baseline trials) despite assertions of invisibility. Not only were our participants' visibility reports unreliable as to task performance, so too, overall, were expressions of confidence. Individually these correlated with task performance during training, and there was an association between training related improvements in task performance and in confidence (see Figure 6f), but these effects were not commensurate. Overall, there was a robust improvement with training in terms of task performance (see Figure 3), averaged across participants, but not in confidence (see Figure 4), or in the number of "seen" trials (see Figure 5). Hence, while our data are consistent with some degree of individual insight into task performance for subliminal inputs (also see Roseboom & Arnold, 2011; Schwiedrzik, Singer, & Melloni, 2009, 2011), they also demonstrate that overall, people's subjective visibility reports are unreliable. What might this signify?

In binocular masking studies people are often asked to report if they can see a stimulus on a trial-by-trial basis. As a guide, they might be shown unmasked targets (as in our feedback condition). They are therefore explicitly encouraged to adopt a criterion reflecting the appearance of an unmasked target stimulus—here a circle, in other studies the appearance of an animal (Lipp et al., 2014; Raio et al., 2012), a face (Jiang & He, 2006; Williams et al., 2004), or some other recognizable form or object (Fang & He, 2005; Ludwig et al., 2013). It is possible this practice is misleading—that people accurately report not having seen such a stimulus, and instead base their responses on the task that reveals sensitivity on some other, possibly subtle and hard to describe, aspect(s) of stimulus appearance. For instance, binocular masking can be associated with an impression of luster (Formankiewicz & Mollon, 2009; Helmholtz, 1924), which could conceivably reveal the location of a masked target. The implication is that dissociations between different measures of visual processing might arise due to mismatched criteria (Campion, Latto, & Smith, 1983; Gallagher & Arnold, 2014; Macmillan & Creelman, 1991), for reporting visibility (can I see the designated target stimulus?), and for guiding performance (is there any impression of a difference whatsoever?). Experimenters might inadvertently encourage this by repeatedly drawing attention

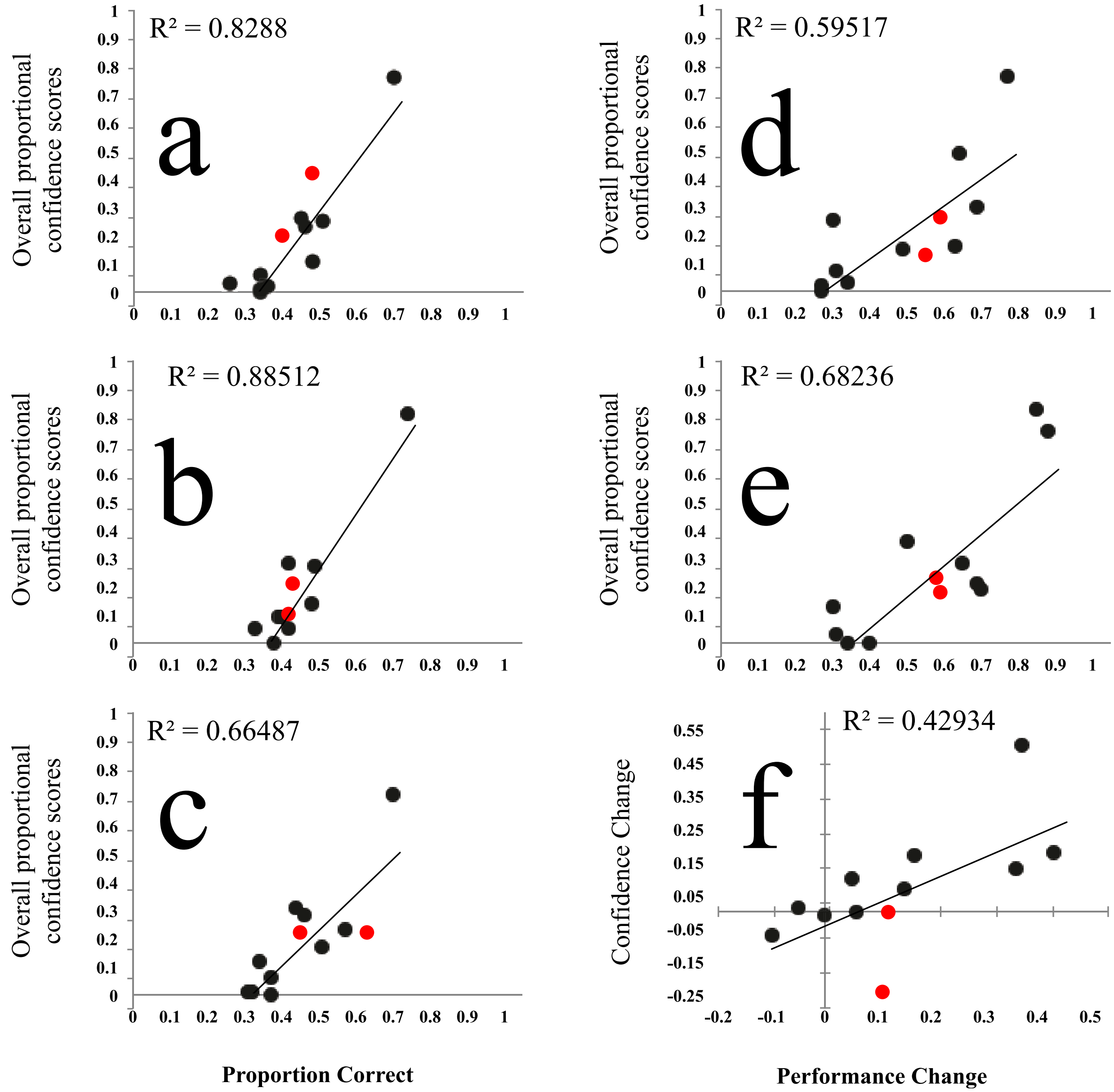

Figure 6. Proportion confidence/proportion correct task performance correlations. Panels a to e depict data from Training Days 1 to 5, respectively. Panel f depicts the correlation between *changes* in task performance and confidence, from Training Day 1 to 5. Author data points in all panels are colored red.

to a sensation (of an unmasked stimulus) that is not experienced during the critical testing phase.

A variable mismatch, between information used for guiding task performance and information used for reporting on confidence (see Spence, Dux, & Arnold, 2016), could explain some of the discrepancies between results on our different measures. Task performance and levels of expressed confidence were, to some extent, related. People who performed better in the pointing task tended to express greater confidence (see Figure 6a through e), and people who evidenced a greater improvement in performance with training tended to evidence a greater increase in confidence with training (see Figure 6f). These data suggest people who were more likely to base confidence and pointing behavior on the same source(s) of information performed better and improved more with training. Other analyses, however, revealed inconsistencies. When confidence was examined in isolation, across participants there was no robust statistical evidence for an increase in confidence (see Figure 4 and associated text), or for an increase in proportion of "seen" trials (see Figure 5 and associated text) with training, despite robust improvements in task performance (see Figure 3 and associated text). Such a scenario could ensue if the information used for judging confidence was at least partially

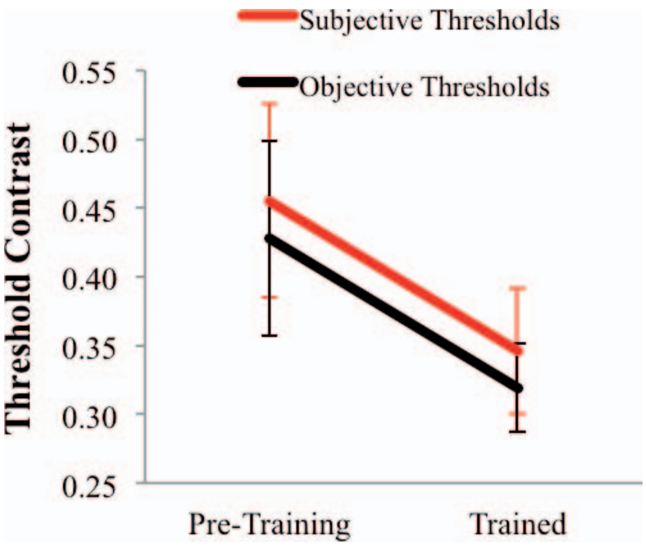

Figure 7. Threshold contrasts, averaged across participants, for objective task performance (black) and for subjective target visibility (red) pre- and posttraining. Error bars depict ± 1 *SEM*.

dissociable from that which governed pointing behaviors. If confidence were based solely on the information that guided pointing, we would have expected to see *commensurate* changes in confidence and pointing.

One could suggest that training independently impacted pointing behavior for subliminal targets and the neural computations that underlie objective sensitivity to binocularly masked targets—that the effects of training on these two measures was unrelated. While we think this is unlikely, our data are correlational, so we cannot draw firm conclusions regarding causal relationships. We note, however, that training resulted in enhanced objective sensitivity to binocularly masked images, and that overall these were commensurate with subjective visibility improvements (see Figure 7 and related text). Application of Occam's razor thus encourages us to presume that these qualitatively and quantitatively matched changes derived from a common cause, as this necessitates the assumption of a single common causal factor, as opposed to training having a matched impact on two independent processes.

In this study we used a ballistic pointing paradigm, as a previous investigation had suggested this was a superior mode of training (Roseboom & Arnold, 2011). It is possible the efficacy of this paradigm is due to the involvement of a visual system optimized for motor planning (de Gelder & Tamietto, 2008; Perenin & Rossetti, 1996), which has access to a source of visual information little affected by binocular masking (He et al., 2005; but see Hesselmann & Malach, 2011). An alternate possibility is that this mode of training is more engaging, encouraging heightened effort and vigilance. Our data cannot distinguish between these possibilities, but they confirm the efficacy of this mode of training. Note, however, that the efficacy of this form of training would seem to rely on improved encodings of binocularly masked inputs. If this effect is intentionally counteracted, by reducing signal intensity as training progresses, no task performance improvement might ensue (see Ludwig et al., 2013). Reducing signal intensity might, however, be necessary to ensure a continually high proportion of "invisible" trials as training improves sensitivity to binocularly masked targets.

It has been suggested that training of the visuomotor system to interact with unseen targets might only be efficacious if tactile feedback is made available (Whitwell et al., 2014). Our data could be seen as consistent with this premise, as tactile feedback was available from poking the touch screen. That feedback was, however, uninformative as to target location, so one could equally argue that our data show that *informative* tactile feedback is not a necessary precondition for learning to better interact with subliminal targets.

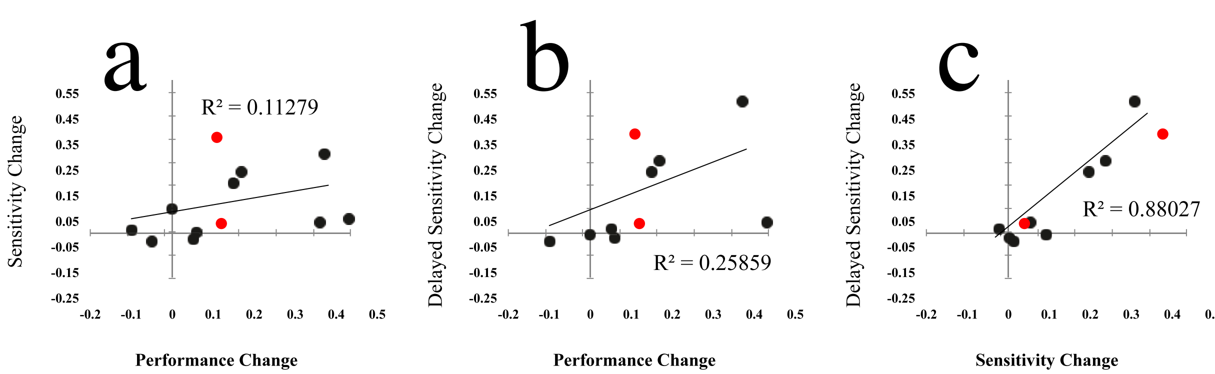

Figure 8. Correlations between changes in pointing accuracy (from Training Day 1 to Training Day 5) and changes in objective detection thresholds from pre- to posttraining immediately after training (a), or ~26 weeks after training (b), along with the correlation between thresholds taken immediately after training and thresholds measured ~26 weeks later (c). Author data points are colored red in all panels.

Moreover, in a previous related study people were trained to reach toward and to place the fingers of their hand in between a pair of binocularly masked oriented lines. In that context there was no tactile feedback at all, but people evidenced conceptually similar improvements in task performance (Roseboom & Arnold, 2011).

Our data show that training to reach and touch binocularly masked targets can improve both performance on this task and objective sensitivity to the positions of binocularly masked images (also see Ludwig et al., 2013). How might encodings of binocularly masked inputs be strengthened with training? Neural responses to target stimuli could be strengthened at early stages of visual encoding, prior to binocular interactions (see Arnold, James, & Roseboom, 2009; Arnold & Quinn, 2010, for evidence highlighting the importance of monocular coding in this context). A plausible mechanism would be an increase in neural gain for masked signals (Salinas & Thier, 2000). It has been argued that this might underlie other training related changes in sensitivity (Miller, Wallis, Bex, & Arnold, 2015). Alternatively, binocular interactions could be modulated, with targets subject to less masking posttraining. Of the two possibilities, we favor the latter. A standard treatment for children with amblyopia is to patch their dominant eye, thereby encouraging reliance on input from the other eye that had previously been subject to persistent binocular masking (for a review see Webber & Wood, 2005). This situation seems analogous to our training effects, and it is consistent with the strength of binocular masking being malleable. We plan to assess this possibility in future experiments.

Keywords: visual awareness, binocular masking, perceptual learning, continuous flash suppression

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