Perceptual learning, aging, and improved visual performance in early stages of visual processing

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In the present study, we examined whether perceptual learning methods can be used to improve performance of older individuals. Subjects performed a texture discrimination task in the peripheral visual field and a letter discrimination task in central vision. The SOA threshold was derived by presenting a mask following the stimuli. Older subjects (age greater than 65 years) were either trained for 2 days using near threshold stimuli (experimental group) or were trained with the task with supra-threshold stimuli (older control group). The experimental group showed significant improvement in the task as a result of training whereas the older control group showed no significant improvement. The improved performance post-training equaled that of a younger control group and was maintained for at least 3 months. The results of two additional experiments indicate that the improved performance was not due to changes in divided attention, that the effect of perceptual learning was location specific, and that the pattern of learning was similar to that of younger subjects. These results indicate that perceptual learning with near threshold training can be used to improve visual performance among older individuals, that the improvements are not the result of practice with the visual task, and that the improvements do not transfer to non-trained locations.

Keywords: perceptual learning, aging, improved visual performance

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Introduction

A considerable body of research has demonstrated age-related changes in vision. This literature has shown performance decrements as a function of age for a wide range of visual functions including contrast sensitivity (Derefeldt, Lennerstrand, & Lundh, 1979; Richards, 1977), dark adaptation (Domey, McFarland, & Chadwick, 1960; McFarland, Domey, Warren, & Ward, 1960), visual acuity (Chapanis, 1950; Kahn et al., 1977), spatial vision (Sekuler, Hutman, & Owsley, 1982), orientation (Betts, Sekuler, & Bennett, 2007), dynamic visual acuity (Long & Crambert, 1990), visual masking (Atchley & Hoffman, 2004), motion perception (Andersen & Atchley, 1995; Atchley & Andersen, 1998; Bennett, Sekuler, & Sekuler, 2007; Betts, Taylor, Sekuler, & Bennett, 2005; Gilmore, Wenk, Naylor, & Stuve, 1992; Trick & Silverman, 1991), optical flow (Andersen & Atchley, 1995; Andersen & Enriquez, 2006; Andersen, Cisneros, Atchley, & Saidpour, 1999), stereopsis (Norman et al., 2008), texture, (Norman, Crabtree, Bartholomew, & Ferrell, 2009), and functional visual field (Ball, Beard, Roenker, Miller, & Griggs, 1988; Keltner & Johnson, 1986; Scialfa, Kline, & Lyman, 1987; for thorough reviews, see Owsley & Sloane, 1990; Sekuler, Kline, Dismukes, & Adams, 1983). Age-related declines in vision can be the result of a variety of factors including optical, retinal, and cortical changes that occur with increased age. Although each of these factors can contribute to age-related declines in function, a growing body of research suggests that the declines are primarily the result of cortical changes (see Spear, 1993 for a detailed review). For example, studies have found evidence of age-related degeneration in intracortical inhibition in V1 (Leventhal, Wang, Pu, Zhou, & Ma, 2003; Schmolesky, Wang, Pu, & Leventhal, 2000; see also Hua et al., 2006) and in temporal processing speed in areas 17 and 18 (Mendelson & Wells, 2002). The finding of age-related changes in cortical function are quite surprising given that studies examining both neural morphology and neural

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density have found no significant changes in visual cortex with increased age (Peters, Feldman, & Vaughan, 1983; Peters, Nigro, & McNally, 1997), suggesting a possible role of biochemical changes. Consistent with this view, recent research (Roberts et al., 2005) has found that acetylcholine (ACh) regulates spatial integration in primary visual cortex suggesting that changes of ACh may account for some of these effects.

Given the widespread nature of age-related declines in visual function, an important issue is whether the loss of visual function can be recovered. One promising approach that might be useful in ameliorating age-related declines in visual function is perceptual learning-improved visual task performance with practice. A number of studies have found evidence of PL for college-age subjects: performance of a perceptual task is enhanced as a result of repeated exposure or training (Ball & Sekuler, 1987; Dosher & Lu, 1998; Fahle & Poggio, 2002; Karni & Sagi, 1991, 1993; Poggio, Fahle, & Edelman, 1992; Seitz & Watanabe, 2003; Watanabe, Nanez, & Sasaki, 2001).

While performance enhancement itself does not directly indicate which stage of visual processing is modified, a high degree of specificity of PL for certain stimulus attributes has been regarded as evidence that PL modified low-level visual stages. It has been shown that some types of PL are specific to the eye that was training. This specificity has been regarded as evidence that the learning would modify V1, since cortical areas beyond V1 in the visual hierarchy contain few cells that have monocular receptive fields (Karni & Sagi, 1991). Studies have also found results showing specificity of learning to a specific retinotopic location (Ahissar & Hochstein, 1997; Fahle & Edelman, 1993; Fiorentini & Berardi, 1980; Karni & Sagi, 1991; McKee & Westheimer, 1978; Poggio et al., 1992; Saarinen & Levi, 1995; Sagi & Tanne, 1994; Shui & Pashler, 1992; Watanabe et al., 2002) or primitive stimulus attributes such as orientation (Fiorentini & Berardi, 1980; Nishina, Seitz, Kawato, & Watanabe, 2007; Poggio et al., 1992; Schoups, Vogels, & Orban, 1995). PL that is specific to retinotopic location or specific to a primitive stimulus attribute is thought to be mediated by cells in early visual areas that have small receptive fields and have high specificity for the stimulus attributes that produce a response (Fiorentini & Berardi, 1980; Karni & Sagi, 1991; McKee & Westheimer, 1978; Sagi & Tanne, 1994; Schoups et al., 1995; Watanabe et al., 2002). Evidence supporting an early stage impact of PL has been found in studies of electrophysiology with animals and functional imaging with humans. Specifically, studies have found changes in neuronal activity of cells in V1 with monkeys (Schoups, Vogels, Qian, & Orban, 2001) and found changes in fMRI signal in V1 with humans (Furmanski, Schluppeck, & Engel, 2004; Schwartz, Maquet, & Frith, 2002; Walker, Stickgold, Jolesz, & Yoo, 2005; Yotsumoto et al., 2009; Yotsumoto, Watanabe, & Sasaki, 2008) that are correlated with improved performance from PL. Other electrophysiological studies, however, have suggested that the relationship of PL and processing in the earliest visual areas, such as V1 and V2, is less clear (Ghose, 2004; Ghose, Yang, & Maunsell, 2002).

Despite the extensive research on PL with college-age subjects, few studies have examined the effects of PL on early sensory processing in older subjects. Ratcliff, Thapar, and McKoon (2006) found evidence of PL in brightness discrimination and letter discrimination tasks with masking. They proposed a diffusion model that separates age-related improvement from practice into non-decisional (concerned with the accumulation of information over time) and decisional (concerned with criterion settings for the decision) components. However, their analysis is based on speeded response tasks in which subjects were instructed to respond either as quickly as possible or as accurately as possible. As a result, their model is informative about general effects of processing speed but not informative about the effects of PL on processing in early levels of visual cortex. Richards, Bennett, and Sekuler (2006) found that repeating training with the useful field of view (UFOV) task resulted in improved performance in divided attention for older observers. Their results indicate that the spatial extent of the UFOV increased (indicating greater function of divided attention) for older observers following 4 days of training and the improved ability to divide attention was retained for up to 3 months. Mayhew, Li, Sotrrar, Tsvetanov, and Kourtzi (2010) examined the effects of training in the perceptual categorization of glass patterns (radial vs. circular patterns). Their results indicate that training changed the decision criterion (the category boundary) for both younger and older observers for discriminating circular and radial glass patterns. In addition, fMRI data indicated changes in occipital–temporal and posterior parietal regions as a result of training for both younger and older observers. Finally, in a non-visual perception study, Peelle and Wingfield (2005) examined age-related differences in PL concerned with compressed speech. Their results indicate that older subjects learned to recognize compressed speech at a rate and magnitude comparable to younger subjects when the stimuli were set to equal levels of accuracy. However, older subjects failed to show evidence of learning transfer to different speech rates. Older subjects also showed a limited ability to continue to improve performance beyond 20 sentences and to retain learning over time. They concluded that the initial improvement from PL is the same for both older and younger subjects, but that age-related declines exist for maintenance and transfer of learning. Thus, none of these studies has shown the involvement of early sensory stages in PL among older individuals.

In the present study, we examined the effectiveness of PL to improve vision in older populations and the possible changes that occur in early visual stages. We used a texture discrimination task based on the study by Karni and Sagi (1991, 1993). This task has been used extensively in PL studies and has been shown to result in location-specific improvements in visual function (Karni & Sagi, 1991) that is associated with activation changes in V1 (Schwartz et al., 2002; Walker et al., 2005; Yotsumoto et al., 2009, 2008). Subjects were presented with stimuli consisting of a centrally presented letter target embedded in a field of horizontally orientated lines (see Figure 1). In addition to the central target, an array of peripherally located lines was oriented diagonally and formed either a vertical or horizontal object. The location of the form was always presented in the same quadrant of the display and was followed by a mask. The subject's task was to identify the central target and the peripherally presented object. In Karni and Sagi's (1991, 1993) study, the SOA between the stimulus and mask was varied to derive an SOA threshold for the orientation discrimination task. We used this paradigm to examine whether age-related differences in SOA thresholds could be improved using PL with near threshold stimuli.

In the first experiment, we examined PL with 18 older subjects (mean age of 71.2). To examine PL with near threshold stimuli, the following methodology was used. Older subjects were randomly assigned to either an experimental or control training group. Each group consisted of 9 older subjects. Subjects participated in 12 training sessions run across 2 days. Each training session consisted of 48 trials in which subjects performed the letter discrimination and texture discrimination tasks. Thresholds were derived for all subjects using a best Parameter Estimation by Sequential Testing (PEST) procedure (Pentland, 1980), which utilizes individual trial responses to derive a psychometric function. To assess the effects of learning, thresholds (the 75% point on the psychometric functions) were derived using the best PEST procedure for each subject at four time intervals: pre-training day 1, post-training day 1, pre-training day 2, and post-training day 2. Feedback was provided for performance on the central task on every trial.

The primary variable of interest was the type of training. The experimental group was given training trials in which the SOA between the stimulus and mask was based on each individual subject's 66% threshold point. The 66% threshold point used for training was based on the threshold derived before the training block. Thus, if performance improved as a result of training, then the SOA should decrease across training blocks. The older control group was given training trials in which the SOA was 2000 ms. Thus, in the experimental group, subjects were given training that included repeated performance of the texture discrimination task and repeated exposure to near threshold stimuli. In the older control group, subjects were given training of repeated performance of the task. To examine whether any improvements in performance were maintained, subjects were tested 3 months following training. In addition, for comparison purposes, a younger control group was run that did not receive training.

Experiment 1

Methods

Subjects

The subjects were 18 older subjects (9 women and 9 men) from the Life Society Program, a continuation education program at the University of California, Riverside and 9 younger subjects (5 women and 4 men) from the University of California, Riverside campus. All were paid for their participation, had normal or corrected-to-normal vision, and were naive with regard to the purpose of the experiment. All subjects were screened using several perceptual and cognitive tests. Demographic information for all subjects is presented in Table 1. In addition, all subjects were pre-screened for eye disease (e.g., glaucoma, macular degeneration, retinitis pigmentosa) and neurological disorders (e.g., Parkinson's disease, Alzheimer's disease, stroke). All subjects signed the subject consent form for the present study approved by the Institutional Review Board of the University of California, Riverside campus.

Apparatus

The displays were presented on a 21-inch (53 cm) flat screen CRT monitor with a pixel resolution of 1280 by 1024 and refresh rate of 120 Hz, controlled by a Windows

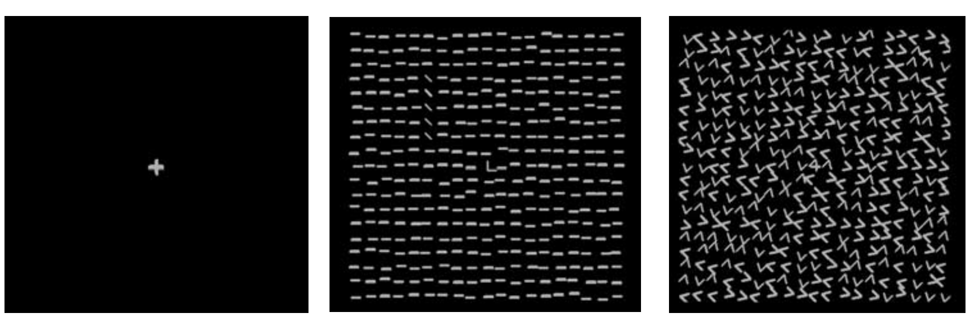

Figure 1. Stimuli used in PL behavioral study. Subjects were shown a fixation cross, followed by a stimulus array containing a central target (T/L) and a peripheral target (vertically oriented diagonal line pattern), followed by a mask.

Variable	Younger *M*	Younger *SD*	Older *M*	Older *SD*
Age (years)[a]	21.3	2.92	71.8	3.93
Years of education[a]	15.3	1.5	16.3	2.1
Snellen letter acuity	10/10.7	1.6	10/11.4	2.6
Log contrast sensitivity[a, b]	1.72	0.12	1.58	0.14
Digit span forward	11.4	2.1	12.3	1.8
Digit span backward	7.4	2.8	8.2	2.0
Perceptual encoding manual[a]	89.1	12.6	66.1	12.2
Kaufman Brief Intelligence Test	27.3	3.8	29.5	3.1

Table 1. Means and standard deviations of participants' demographic information and results from perceptual and cognitive tests. *Note*: [a]Differences between age groups were significant ($p \leq 0.05$) for both sets of age groups. [b]Contrast sensitivity was measured using the Pelli Robson test (Pelli, Robson, & Wilkins, 1988).

XP Professional Operating System on a Dell Dimension XPS workstation. The visual angle of the display was 14 deg by 14 deg and was viewed from a distance of 100 cm through a glass (plano-convex) collimation lens (45.7-cm diameter) to control for age-related differences in accommodative focus. A chin rest was mounted at a position appropriate to this viewing distance and was used to maintain head position.

Stimuli

On each trial, subjects were presented with a sequence of three displays—a fixation display, target display, and mask. The first display was a fixation cross (0.4 by 0.38 deg visual angle) and was presented until the subject initiated the trial. The target display (presented for 100 ms) was a 19 by 19 feature array of horizontal bars (0.41 by 0.02 deg visual angle) that were randomly shifted by 0.25 deg visual angle. At the central position within the array, an L or T was presented. A horizontal or vertical pattern of 5 diagonal lines was presented in the upper right quadrant. The location of the horizontal/vertical pattern was randomized but was always presented in the upper right quadrant. The mask (presented for 10 ms) consisted of randomly oriented V-shaped features (0.41 by 0.36 deg). The subject's task was to indicate whether the central target was either an L or a T and whether the pattern in the upper right quadrant formed a vertical or horizontal line. An auditory tone was used to provide feedback (an incorrect response) for the central letter discrimination response. The stimulus-to-mask onset asynchrony (SOA) was varied and was used to derive a threshold of the temporal limits for target (centrally located letter and peripherally located form) identification. The luminances of the display features and background were 29.5 cd/m^2 and 0.09 cd/m^2, respectively, resulting in a Michelson contrast ratio of 0.99.

Procedure

Older subjects participated in four experimental sessions conducted on separate days during a 1-week period. In session 1, subjects were screened for normal visual and cognitive abilities (see Table 1). Following the screening, subjects were shown examples of the stimuli and were read instructions indicating the two tasks. For the letter discrimination task, subjects were instructed to press with their left hand the "a" key if the letter was an "L" and the "d" key if the letter was a "T". Subjects were given 20 practice trials (without the mask presented) with the letter discrimination task and were required to achieve 90% accuracy before proceeding. For the form discrimination task, subjects were instructed to press with their right hand the "j" key if the form was horizontal and the "l" key if the form was vertical. Subjects were given 20 practice trials (without the mask presented) with the form discrimination task and were required to achieve 90% accuracy before proceeding. Subjects were then given 20 practice trials (without the mask presented) with both tasks and were required to achieve 90% accuracy in both tasks before proceeding. Subjects were then presented with 10 trials with the mask and an SOA of 2000 ms to ensure that subjects were familiar with the display sequence on every trial. After subjects completed task training, an SOA threshold (75% point) was derived using the best PEST procedure. The total time for session 1 was approximately 1 h.

Experimental sessions 2 (training day 1) and 3 (training day 2) were run on consecutive days and consisted of deriving a pre-training threshold, 12 training blocks, and deriving a post-training threshold. Each training block consisted of 48 trials. Subjects in the experimental group received SOA training at the 66% point in their psychometric function based on their threshold derived at the beginning of the session. Subjects in the older control group received training in which the SOA was 2000 ms (well above threshold). The total number of training trials, across experimental sessions 2 and 3, was 1152.

Experimental session 4 occurred 3 months after experimental sessions 2 and 3 and consisted of deriving a 75% threshold using the best PEST procedure. The younger control subjects were only run through experimental session 1.

Results

Overall, subjects were quite accurate in performing the letter discrimination task. The mean percent correct for the letter discrimination task for the experimental and control groups were 96.8 and 98.2, respectively. The results for the SOA thresholds are shown in Figure 2. We have included threshold data without training for 9 younger subjects (mean age of 21.6; younger control experiment) for comparison purposes. There was no

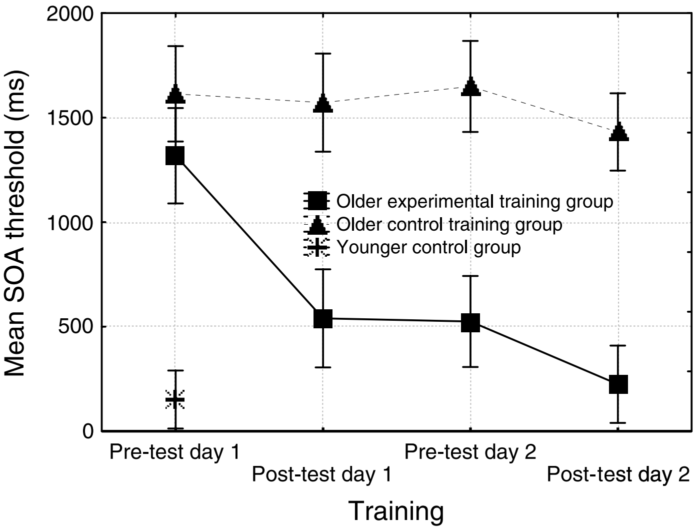

Figure 2. Change in SOA thresholds as a result of training. Separate curves are plotted for older experimental (solid squares) and older control groups (solid triangles). Results for a younger control group (star) is included for comparison purposes.

significant difference in SOA threshold between the older experimental and older control groups prior to training (pre-test day 1; $t(16) = 0.78$, $p > 0.05$). The two-way interaction of training and group type (experimental/control) was significant, $F(3,48) = 6.2$, $p < 0.05$ (see Figure 2). According to this result, discrimination performance significantly improved for the older experimental group as a result of training ($F(3,28) = 9.7$, $p < 0.01$). However, discrimination performance did not significantly improve for the older control group as a result of training ($F(3,28) = 1.63$, $p > 0.05$). This result suggests that repeated performance of the task is not sufficient for improving visual processing. Instead, improvement only occurred when subjects were trained with near threshold stimuli. A comparison between older and younger subjects indicated that prior to training the older experimental ($t(16) = 4.0$) and older control ($t(16) = 5.3$) groups had significantly higher thresholds than younger subjects ($p < 0.01$). Following training, the older control group had significantly higher thresholds than the younger control group without training ($t(16) = 4.1$, $p < 0.01$). However, following training thresholds for the older experimental group was not significantly different from the younger control group without training ($t(16) = 0.47$, $p > 0.05$). These results indicate that visual performance for older subjects improved as a result of PL resulting in performance that was similar to the performance of the younger control group. This finding demonstrates that PL training can be used to recover from age-related declines in vision.

To determine whether learning was retained over a long duration, we conducted a 3-month follow-up study with a subset of the subjects used in the main experiment. For the follow-up study, we were able to run 6 of the 9 subjects in the older experimental training group, 7 of the 9 subjects in the older control training group. An analysis of the results indicated no significant difference between these groups on pre-test day 1 ($t(11) = 1.12$. $p > 0.05$), a significant difference between these groups on post-test day 2 ($t(11) = 3.09$, $p < 0.05$), and a significant difference between these groups assessed 3 months after training ($t(11) = 2.26$, $p < 0.05$). Mean thresholds assessed post-test day 2 were 1268 and 63 ms for the control and experimental groups, respectively. Mean thresholds assessed 3 months after training were 1054 and 110 ms for the control and experimental groups, respectively. These results indicate that the improved performance from PL training was retained over a 3-month period and thus is regarded as a manifestation of long-term improvement rather than mere short-term sensitization.

Experiment 2

An important issue is whether other factors independent of visual cortical processing might underlie the improved performance for older observers as a result of perceptual learning. One possibility is that presenting older observers with near threshold stimuli results in improved allocation of attention to perform the tasks. It is well documented in the literature that older observers have a decreased ability to attend to visual stimuli (see Kramer & Madden, 2008 for an excellent review). This issue has been studied in a variety of contexts including divided attention. Studies of divided attention have shown that when older subjects respond to a centrally located target they have a decreased ability to process information in the peripheral visual field. This issue has been referred to as the useful field of view (Ball & Owsley, 1993) and has been argued to be an important predictor of increased crash risk among older drivers (Owsley, Ball, McGwin, & Slaon, 1998). In addition, as discussed earlier, studies have found that the useful field of view of older subjects can improve with training (Richards et al., 2006). This result suggests that the improved performance of older subjects in Experiment 1 might be due to improved divided attention.

To assess this issue, we tested divided attention using the UFOV test and texture discrimination over 4 days. On the first day (pre-training day 1), subjects were instructed and received practice on the texture discrimination task. At the end of day 1, texture discrimination thresholds and UFOV thresholds were derived. In days 2 and 3, subjects received PL training and texture discrimination thresholds and UFOV thresholds were derived. On day 4, texture discrimination thresholds and UFOV thresholds were derived to account for any consolidation effects of perceptual learning that might occur (Karni, Tanne, Rubenstein, Askenasy, & Sagi, 1994). If improved performance in the texture discrimination task was to due to an increased performance in divided attention, then we should find an improved performance in UFOV as a result of training.

Methods

Subjects

The subjects were 8 older subjects (4 women and 4 men) from the Life Society Program who had not participated in Experiment 1. All were paid for their participation, had normal or corrected-to-normal vision, and were naive with regard to the purpose of the experiment. All subjects were screened using several perceptual and cognitive tests (see Table 1) and were pre-screened for eye disease (e.g., glaucoma, macular degeneration, retinitis pigmentosa) and neurological disorders (e.g., Parkinson's disease, Alzheimer's disease, stroke). All subjects signed the subject consent form for the present study approved by the Institutional Review Board of the University of California, Riverside campus.

Apparatus

The same apparatus was used as in Experiment 1.

Procedure

The stimuli and apparatus for the texture discrimination task were identical to that used in Experiment 1. The UFOV test (Model 2000; Ball & Owsley, 1993) is a computerized assessment of divided visual attention in which subjects perform an object identification task (located in the center of the display) and a second object location task (positioned in one of 24 peripheral locations along eight radial spokes at three eccentricities (10, 20, and 30 degrees)). For the object identification task, subjects are presented either a car or truck. For the location task, subjects identify which radial spoke a car was presented. The current study used subtest 3 of the UFOV test in which the central and peripheral targets are presented in a field of distractors (triangles randomly presented in the display). Duration thresholds were derived based on 75% performance for the peripheral task. Performance on the primary central task was greater than 90%.

The procedure was the same as in Experiment 1 with the following exceptions. Subjects received 10 training blocks (5 per training day) on day 2 and day 3 of the study. Each training block consisted of 16 trials of stimuli at the 80%, 75%, 70%, 65%, and 60% points in descending order based on each subject's psychometric function. The specific training values in a block were based on a derived psychometric function from performance on the previous block. The total number of training trials was 800. A final threshold was derived on days 2 and 3 following training. In addition to deriving the texture discrimination threshold at the end of each day, we also measured divided attention using the UFOV test at the end of each day. Data were collected on 4 days (pre-training day 1, training day 2, training day 3, post-training day 4) within a 1-week period.

Results

Overall accuracy for the letter discrimination task was 97.4%. The results for the SOA thresholds are shown in Figure 3. Consistent with the results of the first experiment, we found a significant improvement in the texture discrimination task as a result of training ($F(3,21) = 12.5$, $p < 0.05$). However, we found no significant change in divided attention as a result of training ($F(3,21) < 1$, $p > 0.05$). These results indicate that while training with near threshold stimuli can improve performance the improved performance was not associated with changes in divided attention.

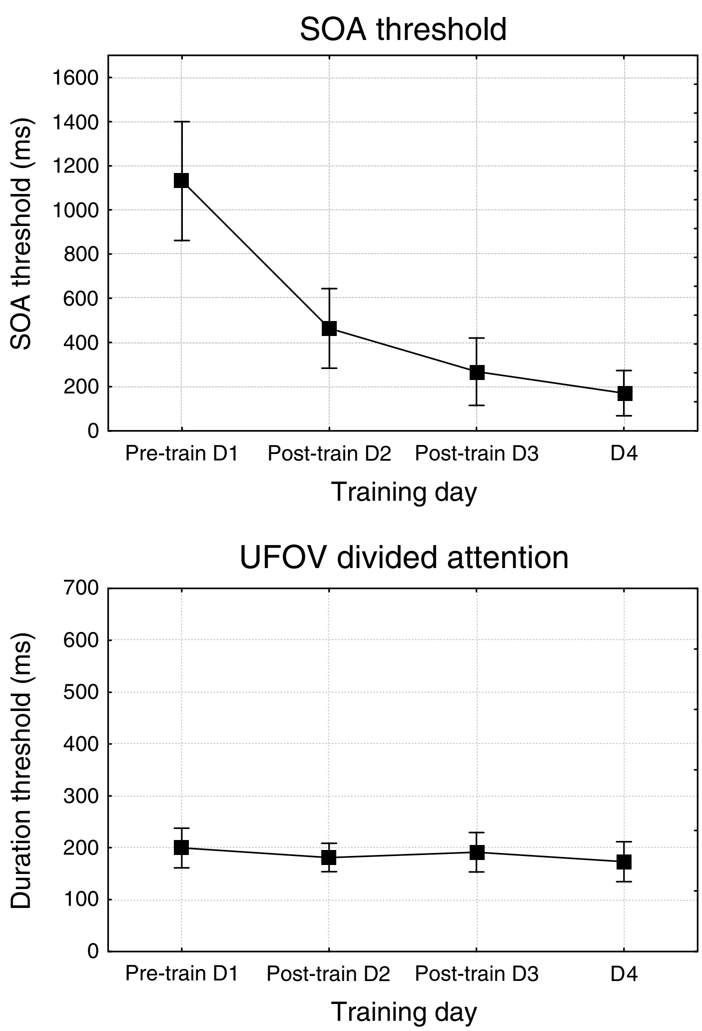

Figure 3. Change in SOA thresholds and divided attention as a result of training.

Experiment 3

Previous research on PL using the texture discrimination task has found that the improved performance is location specific (Karni & Sagi, 1991). In these studies, subjects were presented PL stimuli in a specific quadrant of the visual field and tested pre- and post-training in the trained quadrant as well as in a non-trained quadrant. The results indicate that prior to training there was no significant difference between trained and non-trained quadrants before learning. However, after training the subjects showed significant improvements only in the quadrant used in PL training. These results have been argued to indicate changes in early levels of visual cortical regions such as V1. In a third experiment, we trained observers with the texture discrimination task in a specific quadrant in the visual field and tested texture discrimination performance in the trained and non-trained quadrants pre- and post-training. In addition, we collected data on younger college-age subjects to determine whether the learning rates obtained with older observers were similar to the learning rates of younger subjects. The results of Experiment 1 indicate that the stimuli used were very easy for younger subjects. In order to produce a similar starting point for older and younger subjects, prior to training, we increased the task difficulty for younger subjects by decreasing the display duration and reducing the size of the texture pattern.

Methods

Subjects

The subjects were 7 older subjects (4 women and 3 men) from the Life Society Program and 9 younger subjects (4 women and 5 men) from the University of California, Riverside campus who had not participated in Experiment 1 or 2. Data for 2 additional older subjects were not included because of difficulty with the task on day 1. All were paid for their participation, had normal or corrected-to-normal vision, and were naive with regard to the purpose of the experiment. All subjects were screened using several perceptual and cognitive tests (see Table 1) and were pre-screened for eye disease (e.g., glaucoma, macular degeneration, retinitis pigmentosa) and neurological disorders (e.g., Parkinson's disease, Alzheimer's disease, stroke). All subjects signed the subject consent form for the present study approved by the Institutional Review Board of the University of California, Riverside campus.

Procedure

The stimuli were the same as that used in Experiment 1 with the following exceptions. To increase task difficulty for younger subjects, the display duration was reduced to 10 ms (for older subjects, the duration was 100 ms), the horizontal/vertical texture pattern was based on 3 diagonal lines (for older subjects, the pattern was based on 5 diagonal lines), and the centrally located T and L were rotated ±25 degrees. The duration, texture pattern, and L and T stimuli for younger subjects were the same as that used in the study by Karni and Sagi (1991). For all subjects, the trained location was the upper right quadrant and the untrained location was the upper left quadrant. The training protocol used was the same as that used in Experiment 2.

Data were collected on 4 days (pre-training day 1, training day 2, training day 3, post-training day 4) within a 1-week period. Thresholds for the trained and untrained locations were derived on pre-training day 1 and post-training day 4. Thresholds for the trained location were derived at the end of training day 2 and training day 3.

Results

The average percent correct for the letter discrimination task was 96.4 and 98.7 for the older and younger subjects, respectively. The results for the SOA thresholds are shown in Figure 4. Both older ($F(3,18) = 5.79$, $p < 0.01$) and younger subjects ($F(3,24) = 4.39$, $p < 0.01$) showed learning in the trained location. There was no significant differences in learning between the older and younger subjects ($F(3,42) < 1$), suggesting a similar rate of learning for both groups. As shown in Figure 5, both younger ($F(1,8) < 1$) and older ($F(1,6) = 1.8$) subjects showed no significant difference between trained and untrained quadrants prior to training. However, both younger ($F(1,8) = 5.6$, $p < 0.05$) and older ($F(1,6) = 10.1$, $p < 0.01$) subjects showed improved texture

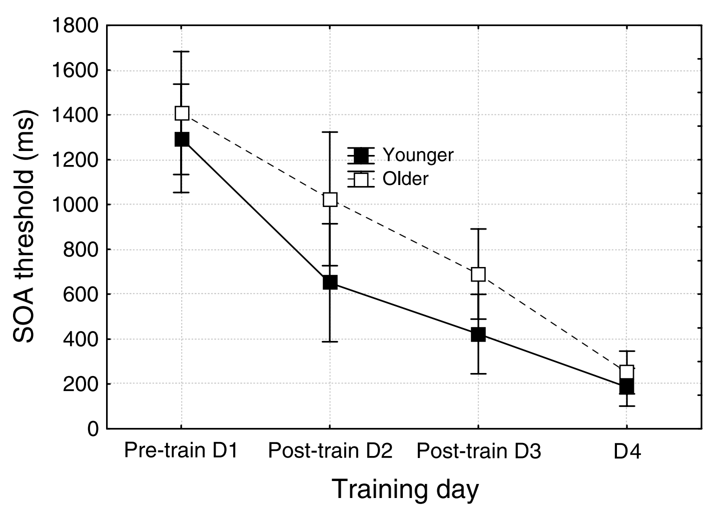

Figure 4. Change in SOA thresholds as a result of training for younger (solid squares) and older (open squares) subjects.

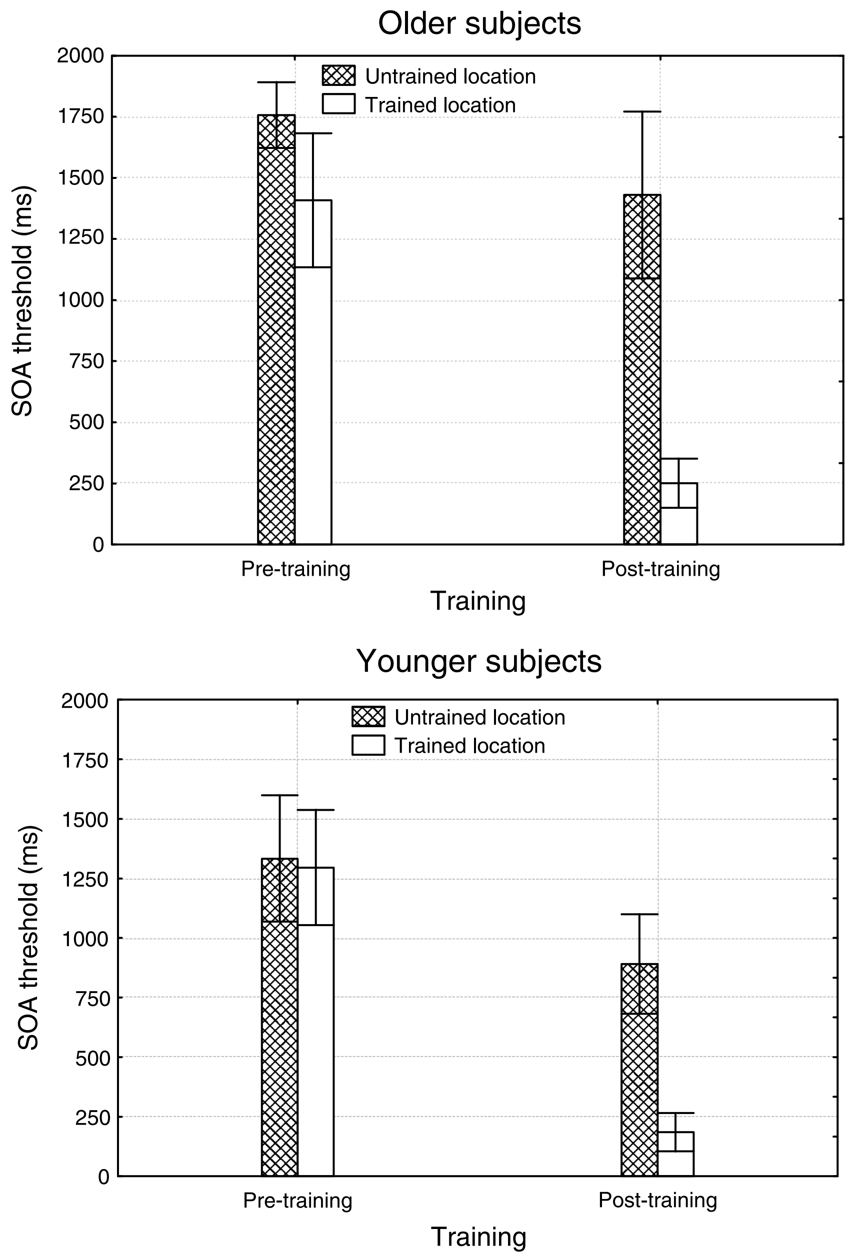

Figure 5. Change in SOA thresholds for trained and untrained locations as a result of training. Top graph is for older subjects. Bottom graph is for younger subjects.

discrimination in the trained quadrant, as compared to the untrained quadrant, as a result of training. The finding that the improved performance is location specific suggests that the changes in perceptual processing may be due to changes in an early visual stage, possibly in V1.

An important issue is whether there were age-related differences in the speed of learning. To assess this issue, we fit each participant's performance to a linear function and derived the slope of the function. These slope values, which represent the speed of learning, were analyzed in a *t*-test to determine whether the speed of learning was different for older and younger participants. The *t*-test was not significant, $t(14) = -0.04$, $p > 0.05$. The average slopes for older and younger participants were −380 and −386 ms, respectively. This result suggests that the speed of learning was similar for older and younger participants.

General discussion

The results of the present study indicate that PL can be used to improve visual function among older individuals. In the first experiment, we examined this issue by training older observers using a texture discrimination paradigm.

Older observers who received 2 days of training with near threshold stimuli showed significant improvement in the texture discrimination task. Older observers who were trained with the task without near threshold stimuli did not improve with 2 days of training. This finding suggests that the results of Experiment 1 were not due to practice or familiarity with the task. Instead, the improved performance was the result of training with difficult near threshold conditions.

We also found that 2 days of training with near threshold conditions for older observers resulted in performance levels, following training, that were similar to a younger group of observers who did not receive training. In addition, the results indicated that the improved performance from PL training was maintained for at least 3 months. These results, considered together, suggest that PL training is a useful method for improving visual performance that has declined due to aging. This conclusion is consistent with the results of other studies that have shown that PL training can be used to improve visual function for clinical groups with visual disorders. For example, PL training has been used to improve visual function for individuals with amblyopia (Polat, Ma-Maim, Belkin, & Sagi, 2004; Polat, Ma-Naim, & Spierer, 2009; see Levi & Li, 2009 for a review) and strabismus (Ding & Levi, 2010). The results of the present study suggest that PL training is also useful for improving visual performance that declines due to normal aging.

It is important to note that the texture discrimination task is a divided attention task in which observers processed and responded to central (letter discrimination) and peripheral (texture orientation) targets. One possible explanation for the improved performance observed in Experiment 1 is that PL training actually improves divided attention. To examine this issue, we trained older observers in the texture discrimination task and measured divided attention across training days. The results indicated improved texture discrimination performance as a result of PL training consistent with the results of Experiment 1. However, we did not find that divided attention, as measured with the useful field of view test, changed as a result of training. Thus, the results of Experiment 2 suggest that improved performance from PL training with near threshold stimuli was not due to changes in divided attention.

Previous research has found that the effects of PL training were specific to the trained location in the visual field. Improved performance in the trained location did not transfer to non-trained locations. This finding has been used as evidence that PL training is the result of plasticity in early levels of visual cortex. In Experiment 3, we examined whether the improved performance in texture discrimination for older observers was location specific. In addition, we examined location-specific performance with younger observers. The results indicated that both younger and older observers showed similar patterns of improved texture discrimination performance with PL training with near threshold stimuli. The improved performance was specific to the trained quadrant in the visual field. It is worth noting that fMRI studies have indicated that PL training using the texture discrimination task (the task used in the present study) is associated with BOLD signal changes specific to the region of V1 that retinotopically corresponds to the trained location (Schwartz et al., 2002; Walker et al., 2005; Yotsumoto et al., 2009, 2008). Thus, our results suggest that improved performance from PL training is similar for both younger and older observers and that the improved performance is consistent with evidence of plasticity in early levels of visual cortex, possibly in V1.

Previous research on PL has found that learning improves as a result of sleep (e.g., Censor, Karni, & Sagi, 2006; Walker & Stickgold, 2005; Walker et al., 2005; Yotsumoto et al., 2009). An important question is whether sleep-dependent learning occurred with older individuals. Although the present study was not designed specifically to examine this issue, one can determine whether sleep-dependent learning occurred by comparing thresholds at the end of a day of training with thresholds on the following day before training. In the present study, three such comparisons can be made. For Experiment 1, sleep-dependent learning can be examined by comparing post-test day 1 with pre-test day 2 (see Figure 2). For Experiments 2 and 3, one can compare post-training day 3 with day 4 (see Figures 3 and 4). The results indicate a 16-ms reduction due to sleep-dependent learning for Experiment 1, a 97-ms improvement for Experiment 2, and a 440-ms improvement for older subjects and a 237-ms improvement for younger subjects in Experiment 3. These results are consistent with the hypothesis that sleep-dependent learning occurred for older individuals. An important issue for future research will be to examine this issue in detail.

However, the possibility that PL with older observers resulted in changes in higher levels of visual cortex cannot be entirely ruled out. Mollon and Danilova proposed a hypothesis that specificity of learning could be due to optical features of retinal images, the local receptor mosaic, or specific wiring in the visual pathways (Mollon & Danilova, 1996). This hypothesis was supported by a recent study that found that some "untransferable" learning (e.g., orientation and vernier discrimination learning) could be transferred to the untrained locations if irrelevant features were trained in that visual field (Xiao et al., 2008). Moreover, recent models have suggested that specificity of learning can be due to reweighting the decision network as well as modifying sensory units (Law & Gold, 2009; Petrov, Dosher, & Lu, 2005). As discussed earlier, fMRI studies have found enhancement in the trained region of the primary visual cortex in association with PL of a texture discrimination task with younger subjects (Schwartz et al., 2001; Walker et al., 2005; Yotsumoto et al., 2009, 2008). However, there have been no studies demonstrating that the neural mechanisms for

PL of a texture discrimination task are the same between younger and older observers. Thus, if the mechanisms are significantly different, it is possible that PL of a texture discrimination task may occur in higher levels of visual cortex.

The results of the three experiments, considered together, indicate considerable improvement of visual performance of older individuals. All of the older participants who received PL training, across all three experiments, showed improvement in the texture discrimination task. We found that 2 days of PL training with near threshold stimuli resulted in thresholds equivalent to younger college-age subjects and were maintained for 3 months. In addition, the improved performance was not associated with a change in divided attention and the improved performance was location specific. It is worth noting, however, that the finding that improved performance was location specific suggests that the use of PL as a therapy to improve age-related declines in vision will require more training (e.g., training across all quadrants of the visual field) than was used in the present study. Given the clear impact of age-related declines in vision on driving, mobility, and falls, the present study suggests that PL may be a useful tool for improving the health and well-being of an older population.

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