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Visual training improves perceptual grouping based on basic stimulus features

Daniel D. Kurylo¹ · Richard Waxman² · Rachel Kidron² · Steven M. Silverstein³

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Abstract Training on visual tasks improves performance on basic and higher order visual capacities. Such improvement has been linked to changes in connectivity among mediating neurons. We investigated whether training effects occur for perceptual grouping. It was hypothesized that repeated engagement of integration mechanisms would enhance grouping processes. Thirty-six participants underwent 15 sessions of training on a visual discrimination task that required perceptual grouping. Participants viewed 20×20 arrays of dots or Gabor patches and indicated whether the array appeared grouped as vertical or horizontal lines. Across trials stimuli became progressively disorganized, contingent upon successful discrimination. Four visual dimensions were examined, in which grouping was based on similarity in luminance, color, orientation, and motion. Psychophysical thresholds of grouping were assessed before and after training. Results indicate that performance in all four dimensions improved with training. Training on a control condition, which paralleled the discrimination task but without a grouping component, produced no improvement. In addition, training on only the luminance and orientation dimensions improved performance for those conditions as well as for grouping by color, on which training had not occurred. However, improvement from partial training did not generalize to motion. Results demonstrate that a

training protocol emphasizing stimulus integration enhanced perceptual grouping. Results suggest that neural mechanisms mediating grouping by common luminance and/or orientation contribute to those mediating grouping by color but do not share resources for grouping by common motion. Results are consistent with theories of perceptual learning emphasizing plasticity in early visual processing regions.

Keywords Perceptual learning · Perceptual grouping · Perceptual organization

Perceptual learning is described as improved perceptual capacities resulting from repeated engagement in specific tasks (for review, see Watanabe & Sasaki, 2015). Effects of perceptual learning persist beyond transient changes to perception produced by priming and are thought to represent long-term modifications to neural processing. In the visual domain, perceptual learning has been reported for basic capacities, including motion speed and direction (Saffell & Matthews, 2003), contrast sensitivity (Sowden, Rose, & Davies, 2002), Vernier acuity (Skrandies, Jedynek, & Fahle, 2001; Skrandies, Lang, & Jedynek, 1996), perception of stereoscopic stimuli (Skrandies & Jedynek, 1999), orientation (Song et al., 2007), and higher order functions, including object (Furmanski & Engel, 2000) and face recognition (Gold, Bennett, & Sekular, 1999).

Perceptual learning reflects changes to processes associated with stimulus properties and task demands. At a cellular level, perceptual learning reflects plasticity in neural response characteristics, including increased contrast sensitivity (Hua et al., 2010) and sharpening of tuning curves (A. Schoups, Vogels, Qian, & Orban, 2001). Changes also occur among connections linking stimulus components (Crist, Li, & Gilbert, 2001). Perceptual learning thereby improves efficiency in

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encoding and processing, which enhances response to stimuli (Chen et al., 2015; Li, Piech, & Gilbert, 2008).

The level of processing at which plasticity occurs varies with experimental conditions (Fahle, 2005). For some conditions, perceptual learning is highly specific to the stimulus parameters under which training occurred, including spatial position (Crist, Kapadia, Westheimer, & Gilbert, 1997; Dill & Fahle, 1997; A. A. Schoups, Vogels, & Orban, 1995), orientation (Crist et al., 1997; A. A. Schoups et al., 1995), orientation of Vernier stimuli (Shoji & Skrandies, 2006; Skrandies et al., 2001), and spatial frequency (Sowden et al., 2002). Such specificity suggests plasticity within neurons at early levels within the visual processing hierarchy. With other conditions, perceptual learning generalizes beyond stimuli used during training (Z. Liu, 1999; Zhang, Xiao, Klein, Levi, & Yu, 2010), suggesting more widespread effects across neural systems (Chen, Cai, Zhou, Thompson, & Fang, 2016).

Neural models of perceptual learning emphasize interactions across levels of processing, particularly involving feedback from later stages that facilitate stimulus processing at early levels (Chen et al., 2015). The site of plasticity has been proposed to vary with task difficulty (reversed hierarchy theory), where less difficult tasks produce changes to high-order processing, while increased difficulty shifts plasticity to low-level processing specific to stimulus properties (Ahissar & Hochstein, 2004).

Less is known about perceptual learning at the level of perceptual grouping. Unlike forms of perceptual learning reported for basic visual capacities, which characterize change in response properties of neurons, grouping entails interactions among neurons, either by means of coordinated activity or by strengthening connections. Perceptual learning associated with grouping occurs at a subsequent stage of processing and is thereby distinct from initial encoding of stimulus properties. Perceptual grouping follows stimulus encoding and precedes high-order visual functions, such as object recognition and scene categorization. It has been shown that past experience, in terms of familiarity with stimuli, contributes to image segmentation (Vecara & Farah, 1997) as well as grouping disconnected line segments (Kimchi & Hadad, 2002). Further, perceptual grouping may be induced following an associative learning task (Vickery & Jiang, 2009). Effects of experience on grouping have been attributed to feedback from object representations that facilitate grouping at a low level of processing (Kimchi & Hadad, 2002). Proposed neural mechanisms of grouping emphasize integration across stimulus representations by means of modifying intrinsic and long-range connections (Kapadia, Ito, Gilbert, & Westheimer, 1995; Roelfsema & Houtkamp, 2011). Increased connection strength is a fundamental process underlying perceptual learning, suggesting that training on grouping tasks can enhance integration of stimulus components and thereby improve perceptual grouping.

For tasks involving perceptual integration, previous studies suggest that plasticity occurs by means of interactions among stimulus components, and not with encoding of the components. Specifically, training improves contrast detection of Gabor targets in the presence of collinear flankers, compared to orthogonal flankers (Adini, Sagi, & Tsodyks, 2002; Maniglia et al., 2011; Yeotikar et al., 2013). In this case, learning effects that occur among collinear elements suggest enhanced interactions of neurons with shared orientation preference at an early level of processing. Context-dependent learning effects are also found for texture segmentation of oriented line textures, suggesting that training enhances binding among grouped stimulus components by strengthening neural connections (Casco, Campana, Grieco, & Fuggetta, 2004). Perceptual learning also occurs with contour integration, where perceptual learning increased separation limits among contour elements (Kovacs, Kozma, Feher, & Benedek, 1999; Li & Gilbert, 2002). Increasing the extent of local interactions may reflect strengthening intermediate or long-range connections. In each case of perceptual integration, performance change resulting from training appears to target interactions among stimulus components.

Previous studies with nongrouping tasks have not specifically examined perceptual learning related to integration mechanisms. A new approach is presented here that measures the perceived global coherence of stimulus patterns. Participants underwent a training protocol in which patterns progressively increased in their level of ambiguity. Results expand analysis of perceptual learning to perceived integration among stimulus components. It was hypothesized here that training on a grouping task would improve ability to perceptually group spatially isolated stimulus elements. To test this, assessments of grouping ability were made before and after a training protocol. The effects of training on grouping were compared to a control condition in which training did not contain a grouping component. Training effects were examined for grouping that was based upon four stimulus features: luminance, color, orientation, or motion. Each of these features represents a basic domain of visual processing (Van Essen, Anderson, & Felleman, 1992). In addition, performance was assessed for training on two of the four stimulus features in order to examine transference of perceptual learning onto the untrained ones.

Method

Subjects

Thirty-six undergraduate and graduate students participated as volunteers or to receive course credit (mean age = 22.0 years, $SD = 3.05$; age range: 17–27 years; 12 males, 24 females; used best corrected 14-in. visual acuity; no reported abnormalities

in color vision). This research was conducted in accordance with APA standards for ethical treatment of subjects and with the approval of the Institutional Review Board for Human Research of Brooklyn College.

Stimuli

Perceptual grouping stimuli For assessment and grouping training, stimuli consisted of a grid of elements (see Fig. 1a). Based upon similarity among stimulus features, the grid could be perceptually grouped along either columns or rows. Four stimulus features were examined: luminance, color, orientation, and motion. Stimuli were generated by customized computer software (Bukhari & Kurylo, 2008). Display monitors were set to 1024×768 pixel resolution at a refresh rate of 60 Hz, which subtended a 19.3° square field. Luminance was linearized with software adjustment.

Luminance For the luminance condition, stimulus elements consisted of solid squares presented at one of two luminance levels (3.9 and 29.5 cd/m^2 , Michelson contrast = 77%) on a gray background (16.5 cd/m^2). Stimulus elements were solid squares, 0.21° on a side. Perceptual grouping was produced by common luminance along either columns or rows.

Color For the color condition, elements consisted of either red or green squares (CIE-USC coordinates: $u' = 0.368$, $v' = 0.513$ for red, and $u' = 0.132$, $v' = 0.553$ for green). Perceptual grouping was produced by common color along either columns or rows (see Fig. 1, column 2b). Hue and saturation approximated isoluminance, determined in pilot testing. Specifically, hue and saturation was based upon a matching procedure administered in a preliminary test to three subjects who did not participate in grouping training. Observers viewed two adjacent squares that alternated out of phase between red and green. Color squares' outside borders extended to 10.2° , which was smaller than the boundary of stimuli used in grouping. Background luminance for isoluminance testing was the same as that used with grouping stimuli. Subjects adjusted luminance contrast until the alternating pattern was least discernable, thereby estimating isoluminance.

Orientation For the orientation condition, stimuli consisted of a grid of Gabor patches (sinusoidal luminance gratings in a Gaussian envelope) that were oriented either vertically or horizontally. Gabor elements, which modulated from 3.9 to 29.5 cd/m^2 , with a spatial frequency of 2.7, or 2.2 cycles/degree and center-to-center separation of 0.72° , in which approximately 2.5 periods were visible. Discrimination was based upon contour integration of collinear patches that appeared along columns or rows (see Fig. 1, column c).

Motion For the motion condition, stimuli consisted of a grid of squares moving along a diagonal path (either \nearrow , \nwarrow , \swarrow , or \searrow). The luminance of stimulus elements was 29.5 cd/m^2 , presented on a gray background of 16.5 cd/m^2 (Michelson contrast = 28%). Stimuli consisted of five consecutive frames, producing apparent motion for 417 ms, at a rate of $4^\circ/\text{s}$. Each stimulus contained two of the four possible motion directions, selected randomly on each trial. Perceptual grouping was produced by elements moving in the same direction (principle of common fate) along either columns or rows (see Fig. 1, column d). Discrimination was not based upon the direction of the motion (which in all cases followed a diagonal path) but instead was based upon coherence of motion direction.

Control stimuli Participants assigned to control conditions performed a discrimination task that paralleled grouping training but did not contain a perceptual grouping component. For each feature, stimuli consisted of a series of solid lines oriented either vertically or horizontally (see Fig. 1b), selected randomly on each trial. Participants indicated the orientation of the lines.

Control luminance For the luminance condition, participants discriminated solid lines that alternated between dark and light luminance, positioned on a gray background.

Control color For the color condition, stimuli consisted of a series of 20 solid lines that alternated in red and green color.

Control orientation For the orientation condition, stimuli consisted of solid lines on a gray background. Each line was constructed from a strip of dark and light luminance, positioned adjacently along the length of the line

Control motion For the motion condition, stimuli consisted of 20 parallel, solid black lines on a gray background. Lines moved diagonally in one of the four possible directions.

Stimulus organization

Performance was indexed in terms of organization of stimuli. Highly organized stimuli provided robust cues for perceptual grouping, whereas grouping became increasingly ambiguous with more disorganized patterns. Stimulus organization was indexed as the percentage of common elements along columns and rows. Across trials elements became increasingly disorganized, thereby reducing regularities in the pattern. Examples of the luminance condition across levels of stimulus organization are shown in Fig. 2.

The index used here reflects the global organization of an array of elements. These stimuli contain multiple, interspersed patterns that compete for grouping assignment, in which

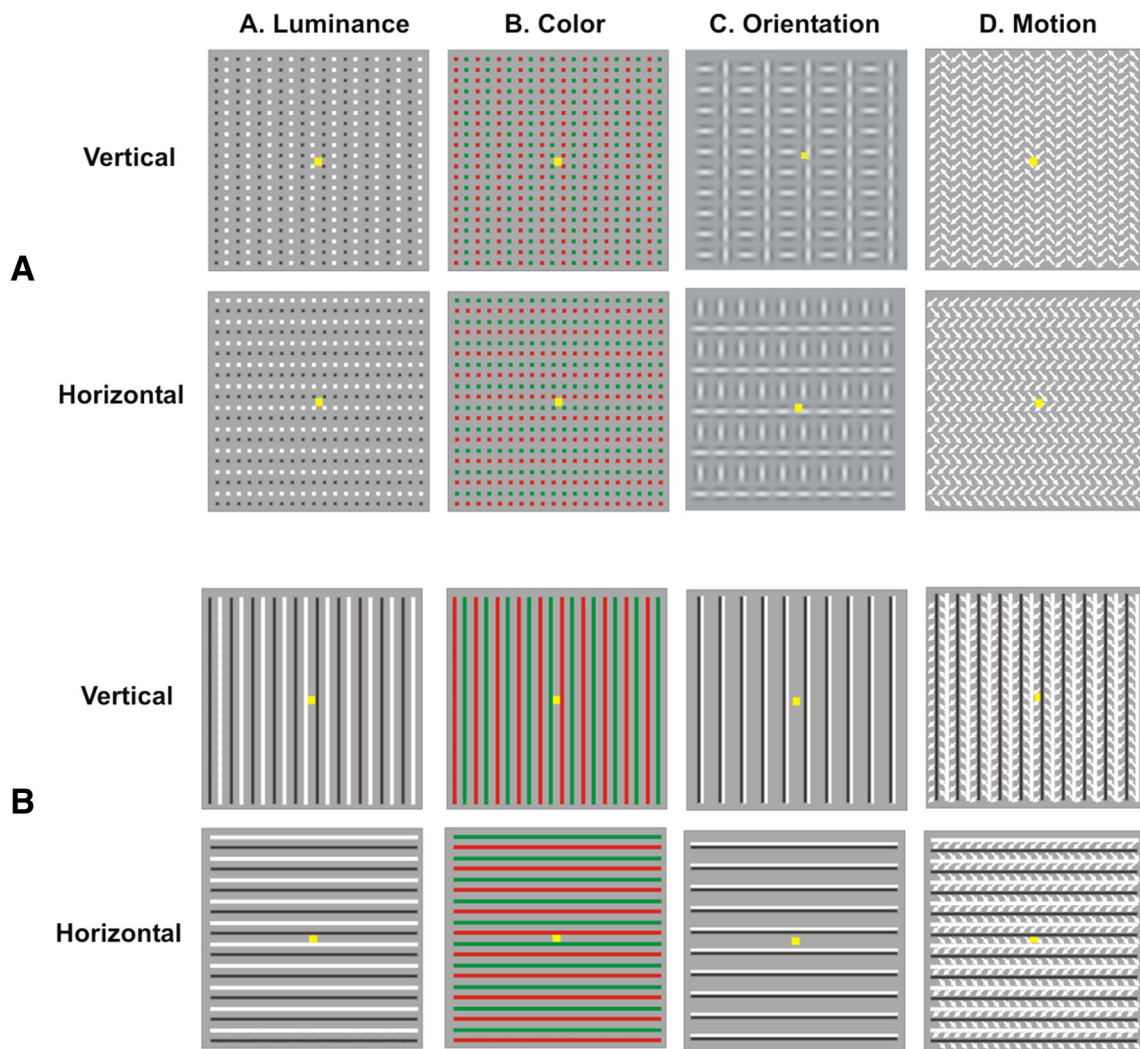


Fig. 1 Examples of each stimulus feature, depicted for both the vertical and horizontal condition. *Dot grids* and *Gabor patches* were used for grouping assessment and training (a) and solid line patterns were used for training with control groups (b). (Color figure online)

specific elements belong to specific grouped forms. Multistable stimuli as those used here produce a global organization that is based upon the cumulative associations among elements.

Procedure

Subjects fixated on a yellow square centered on the computer monitor. A stimulus then appeared for 417 ms (25 cycles at

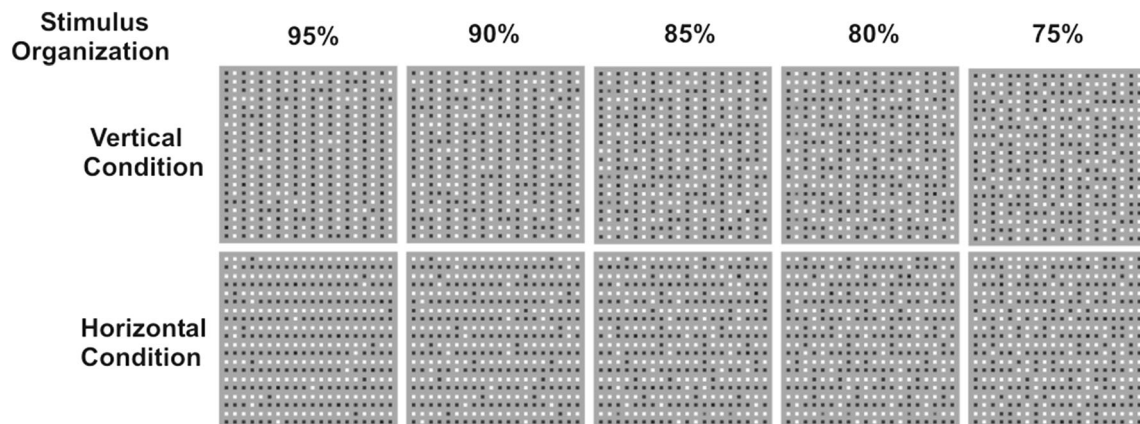


Fig. 2 Examples of the vertical pattern for the luminance condition across levels of stimulus organization

60 Hz). The vertical or horizontal condition was randomly assigned on each trial. Subjects responded by keyboard entry, using their preferred hand, whether the stimulus appeared to be predominantly organized as a vertical or horizontal pattern. If subjects were unsure, they were asked to guess (i.e., two-alternative forced choice), thereby precluding possible response bias. Participants were tested individually. Participants were informed that reaction time was not a factor, and were instructed to optimize accuracy and not speed of responding.

Assessment Before and after the training period, thresholds were determined for each stimulus feature. Thresholds reflect the lowest stimulus organization at which patterns could be perceptually grouped. Thresholds were determined with a descending method of limits. A trial series began with 100% stimulus organization, and organization was reduced by 2% following two consecutive correct responses. The descending series continued until an error was made. Following an error, organization increased by 10%, and the descending series was repeated. Performance limits were recorded as the stimulus organization at which subjects first made an error following a series of two or more correct responses. Thresholds were based on the mean of eight descending series, collected on 2 days. Each session lasted approximately 15 minutes. For assessment, no feedback for correct or incorrect response was given.

Training The term *training* used here refers to the repeated engagement in a perceptual task, including stimulus processing, perceptual decision, and response components. Following the initial assessments, participants underwent 15 days of training. Training occurred three times per week for approximately 45 minutes per session. In each session, participants trained on each of the four stimulus features for 7 minutes. Stimuli for training were similar to those used for assessment. Participants viewed stimuli and indicated the perceived grouping pattern (vertical or horizontal). For training, feedback (correct or incorrect responses) was provided on each trial. For each of the four stimulus features, trials began with highly organized stimuli (easier condition), and increased in difficulty following successful performance. Specifically, performance was determined for each set of 10 trials. Accuracy of 90% or better resulted in increased difficulty by 1%, whereas performance of 70% or less resulted in decreased difficulty by 1%. No change in difficulty occurred for performance between these limits. For each session, starting levels were set to 3% more organized than the final level of the previous session. These rules for assigning organization level ensured that difficulty at the start of a session was within participants' ability, and that difficulty advanced

systematically based upon successful performance at each level.

Participants were assigned to one of three training groups:

- | | |
|--|---|
| Group 1: Full training | For the full training group, subjects underwent training with perceptual grouping stimuli on all four stimulus features. |
| Group 2: Partial training | For the partial training group, subjects underwent grouping training on the luminance and orientation conditions. Although the two stimulus features selected for the partial training condition are associated with distinct encoding properties of stimuli, other combinations of the four stimulus features may be explored in future testing. For the color and motion conditions, participants performed a discrimination task with the solid line, control stimuli. |
| Group 3: Control group (solid line discrimination) | For the control group, participant performed solid line discrimination with the control stimuli for each of the four stimulus features. |

Results

In three cases, assessment scores were beyond three standard deviations below the means of remaining scores and were considered outliers and not included in analysis.

Effects of training on grouping thresholds

Comparisons were made of change in performance between pre- and posttraining assessments (see Fig. 3). A two-way repeated-measure analysis of variance (ANOVA) was performed, with subject group and stimulus feature as factors, and change in performance as the dependent variable. Analysis indicated significant main effects of subject group, $F(2, 33) = 15.09, p < .01, \eta^2 = .478$, and feature, $F(3, 99) = 3.67, p < .05, \eta^2 = .100$, as well as an interaction of group by feature, $F(6, 99) = 2.43, p < .05, \eta^2 = .128$. Post hoc analysis indicated that overall the full training group differed significantly from the control group for each stimulus feature ($HSD = 4.66, p < .05$). Pair-wise comparisons of feature indicated that motion differed from luminance and color ($HSD = 2.45, p < .05$). Examining group differences for each feature separately, the full and partial training groups differed from the control group for luminance, color, and orientation. For

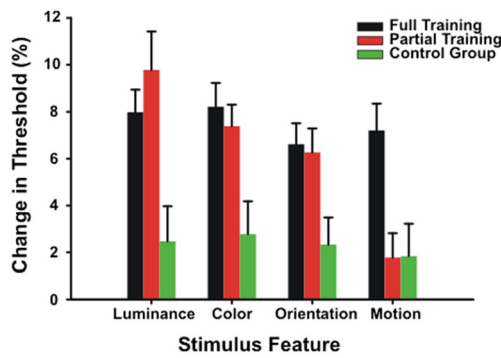


Fig. 3 Change in performance between pre- and posttraining assessments. (Color figure online)

motion, the full training group differed from the partial training and control groups ($HSD = 3.79, p < .05$). Grouping training on the luminance and orientation conditions therefore generalized to color but did not affect performance on motion. In addition, a trend existed for improvement by the control group on each stimulus feature, although performance did not differ significantly from zero.

Relationship between initial performance and training effects

Initial grouping performance (grouping thresholds from the initial assessment) varied widely, with thresholds

ranging from 2.75% to 30.9%. For some stimulus features, participants with lower initial performance displayed greater improvement with training (see Fig. 4). Examining each feature separately, a significant negative correlation existed between initial performance and performance change for the luminance and color conditions, regardless of whether participants received grouping training (see Table 1). For the orientation condition, initial performance did not correlate significantly with performance change for any subject groups. For the motion condition, only the full training group, which received grouping training, showed a significant negative correlation between initial threshold and performance change. The relationship between initial threshold and performance change may reflect a ceiling effect that limited improvement for subjects with high initial performance and allowed greater performance change for those with low initial performance.

Pattern of performance across training sessions

Rate of improvement across sessions was examined for the full training group. Greater improvement occurred early in training and stabilized after approximately 10 days of training (see Fig. 5a). Subdividing sessions into three phases, with 5 days in each phase (see Fig. 5b), the slope of the performance by session

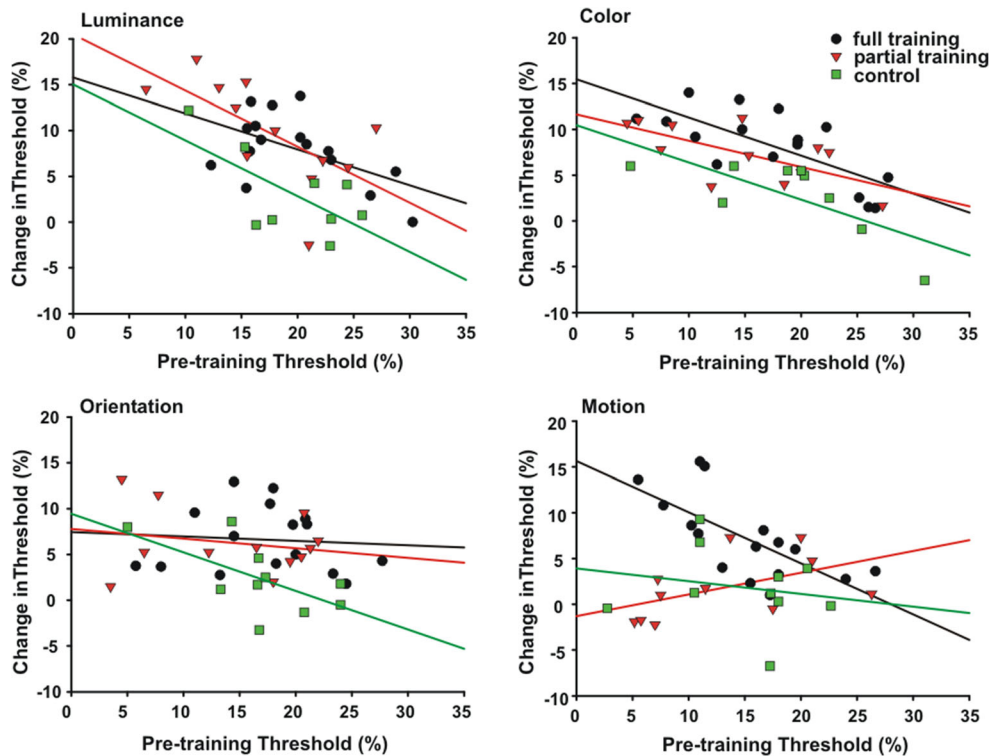


Fig. 4 Relationship between initial performance and change in performance between pre- and posttraining. Linear regressions are fit to each subject group. (Color figure online)

Table 1 Correlation coefficients (Pearson's r) for initial performance and change in performance

	Full training	Partial training	Control group
Luminance	† -.539*	† -.642*	-.659*
Color	† -.726**	-.663*	-.737**
Orientation	† -.081	† -.213	-.614*
Motion	† -.691**	.498	-.190

† received training on dot grouping; * $p < .05$; ** $p < .01$

function, which describes improvement in performance, was greatest during the first phase, was minimal during the second phase, and did not differ significantly from zero in the final phase ($t = 1.13$, $p > .05$).

Discussion

Results indicate that training on a visual discrimination task requiring perceptual grouping improves ability to disambiguate dot patterns. Results expand analysis of perceptual learning to an intermediate level of visual processing where stimulus components are integrated into unified forms. In addition, our findings are consistent with models of neuroplasticity in which top-down factors modulate the feedforward sweep of sensory processing (Chen et al., 2015).

Performance improved for each stimulus feature tested, demonstrating enhanced grouping ability across basic domains of visual processing. Most improvement occurred within the first 10 training sessions, followed by a period of more stable performance. In most cases, participants with reduced initial ability benefitted most from training. Asymptotic performance across sessions suggests a ceiling effect in discriminating stimuli used here, thereby limiting improvement for participants with higher initial performance.

Training restricted to the luminance and orientation condition produced improvement on the color, but not motion,

condition. Luminance and color share some encoding properties (Conway, 2001; Peng & Van Essen, 2004) and are distinguished from encoding of line orientation (Yousef, Kim, Eysel, Toth, & Kisvarday, 1999) and motion direction (Orban, Kennedy, & Bullier, 1986). In addition, mediation of grouping by similarity (Han, Jiang, Mao, Humphreys, & Gu, 2005), which applied to the luminance and color conditions, is distinguished from that of contour integration (Altmann, Bulthoff, & Kourtzi, 2003) and motion coherence (Handel, Lutzenberger, Thier, & Haarmeier, 2007). Properties of encoding and grouping may therefore account for the pattern of transfer in perceptual learning across stimulus features.

Transfer of training effects from luminance onto color may have resulted from common neural mechanisms used to encode these features. Alternatively, the association between luminance and color may reflect shared stimulus characteristics used for grouping. Specifically, for the color condition, hue and saturation approximated isoluminance, based upon preliminary testing with subjects not used in the training condition. In addition, stimuli used to establish isoluminance were more centrally located than stimuli used for grouping. These procedures therefore allow the possibility that some degree of luminance differences existed in the color pair elements, enabling the use of luminance as a grouping cue, and possibly accounting for transfer of training effects between these features.

For training sessions, trial-by-trial feedback of accuracy was provided to guide appropriate grouping selection and enhance effects of training. Although perceptual learning can occur without feedback (Crist et al., 1997; Petrov, Doshier, & Lu, 2006), external feedback is an effective means of enhancing speed of learning and performance accuracy (Herzog & Fahle, 1997), particularly for high levels of difficulty (Seitz et al., 2006) or when performance accuracy is low (J. Liu, Lu, & Doshier, 2010). Feedback in perceptual learning has been associated with reinforcement effects (Herzog & Fahle, 1997). Effects of feedback are proposed to results from pairing a reinforcement signal with a stimulus representation, whether

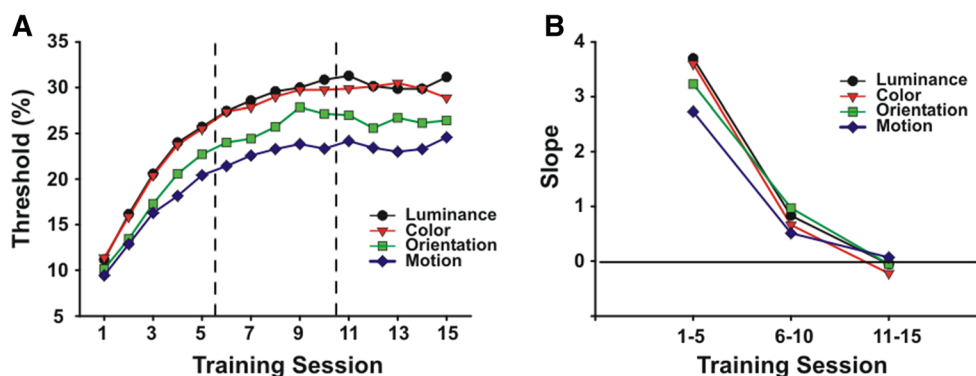


Fig. 5 **a** Peak performance for each stimulus condition as a function of training session. **b** Slope of training function for each 5-day training phase. (Color figure online)

for features perceived as important for task requirements (task relevant) or for unattended features (task irrelevant; A. Seitz & Watanabe, 2005). Including feedback of accuracy as part of the training protocol thereby improves the effectiveness of training.

A trend existed for improvement by control subjects, though to a lesser degree than treatment groups. This effect is apparent with the trend of improvement by the control group for each stimulus feature (see Fig. 4), which was more apparent for subjects with lower initial performance (see Fig. 5, Table 1). Improvement by control subjects may reflect properties of solid-line discrimination that are not associated with perceptual grouping. Training on the solid-line discrimination task appeared to be most beneficial to those who performed less well on initial assessments, suggesting that part of the reduced performance was due to task demands not associated with grouping. Although the control group did not undergo grouping training and the training task was extremely easy, procedures used for control training contained factors that may benefit performance, including gaining familiarity with stimuli and trial events, attending to critical stimulus properties, and discriminating orientation of line patterns. These factors also existed with grouping training, and contributed to improvement found with treatment groups. However, the additional improvement that resulted from grouping training suggests that specific changes occurred to task-relevant processes underlying grouping.

Theories of mechanisms mediating grouping involve interactions among neurons encoding components of grouped forms. By engaging these mechanisms during training, neural interactions may be strengthened. Specifically, response rates increase among neurons responsive to a grouped contour (Roelfsema, Lamme, & Spekreijse, 2004). Grouping training could potentially target neural systems underlying rate increases that mark binding among stimulus components. Similarly, synchronous EEG activity correlate with stimulus ambiguity in a perceptual grouping task (Nicolae, Gepshtein, Gong, & van Leeuwen, 2010). Grouping training may modify systems underlying synchronous activity, such as interactions among brain areas processing global structure. For grouping based upon basic stimulus features, as those used here, grouping is proposed to be reflected by increased response among neurons encoding common features (Roelfsema & Houtkamp, 2011). By engaging enhanced responses during training, connections among associated neurons may be strengthened, thereby increasing efficiency of grouping. For each of these neural mechanisms, engaging grouping may enhance binding among elements with common properties, allowing increased efficiency in perceiving global structure.

This investigation did not explicitly test whether improved performance resulted from enhanced integration of stimulus elements. As such, results may be accounted for by changes to alternative neural mechanisms. One possibility is that training

improved extraction of relevant stimulus signals upon which discrimination is based, thereby reducing noise during stimulus encoding. Another alternative mechanism is that integration of local element strings form oriented patterns, which are processed by orientation-selective neurons. In this case, performance improvement does not require enhanced integration of stimulus components but instead reflects changes to orientation response at an early level of processing.

Assessment of perceptual grouping was based upon stimuli used in training. Results therefore do not explore whether improvement in grouping extends beyond task-specific stimuli, including grouping diagonal or curved patterns. Further investigation of training effects on grouping ability on alternate patterns would further probe specificity of grouping training, and whether effects are restricted to stimulus representations used in training conditions (Crist et al., 1997; A. A. Schoups et al., 1995), or if training affects more general mechanisms (Chen et al. 2016; Z. Liu, 1999; Zhang et al., 2010).

The role this form of plasticity may play in natural vision is to allow adaptive changes across different visual environments. Demands on grouping vary with characteristics of the scene, such as moving patterns in open landscapes, or densely clustered components in confined scenes. Plasticity resulting from exposure to specific stimulus conditions would thereby improve the ability to disambiguate objects within natural scenes containing specific characteristics. In addition, improving performance at the level of perceptual organization could benefit subsequent levels of processing that rely on grouping, including object and facial recognition, reading, and identifying complex visual scenes. Procedures used here may also be applied to clinical populations in which impaired perceptual organization has been identified, including Alzheimer's disease (Kurylo, Allan, Collins, & Baron, 2003; Uhlhaas et al., 2008) and schizophrenia (Silverstein & Keane, 2009, 2011; Uhlhaas & Silverstein, 2005).

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