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Functional consequences of experience-dependent plasticity on tactile perception following perceptual learning

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Abstract

Continuous training enhances perceptual discrimination and promotes neural changes in areas encoding the experienced stimuli. This type of experience-dependent plasticity has been demonstrated in several sensory and motor systems. Particularly, non-human primates trained to detect consecutive tactile bar indentations across multiple digits showed expanded excitatory receptive fields (RFs) in somatosensory cortex. However, the perceptual implications of these anatomical changes remain undetermined. Here, we trained human participants for nine days on a tactile task that promoted expansion of multi-digit RFs. Participants were required to detect consecutive indentations of bar stimuli spanning multiple digits. Throughout the training regime we tracked participants' discrimination thresholds on spatial (grating orientation) and temporal tasks on the trained and untrained hands in separate sessions. We hypothesized that training on the multi-digit task would decrease perceptual thresholds on tasks that require stimulus processing across multiple digits, while also increasing thresholds on tasks requiring discrimination on single digits. We observed an increase in orientation thresholds on a single-digit. Importantly, this effect was selective for the stimulus orientation and hand used during multi-digit training. We also found that temporal acuity between digits improved across trained digits, suggesting that discriminating the temporal order of multi-digit stimuli can transfer to temporal discrimination of other tactile stimuli. These results suggest that experience-dependent plasticity following perceptual learning improves and interferes with tactile abilities in manners predictive of the task and stimulus features used during training.

Keywords

Psychophysics; somatosensory; acuity; learning; human

INTRODUCTION

Continuous training or exposure to a sensory stimulus can enhance perceptual discrimination (Fahle, 2005; Seitz & Watanabe, 2005; Gilbert *et al.*, 2009). This effect, termed perceptual learning, has been extensively investigated in the visual system. Many studies have shown

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that, over time, individuals demonstrate enhanced perceptual abilities in discriminating sensory features such as orientation, motion, and luminance (Fahle *et al.*, 1995; Goldstone, 1998; Seitz & Watanabe, 2005; Gilbert *et al.*, 2009; Sasaki *et al.*, 2010). Cortical changes that are thought to underlie these perceptual improvements are a type of experience-dependent plasticity, and have been extensively observed in visual cortices (Crist *et al.*, 2001; Schoups *et al.*, 2001; Li *et al.*, 2004; Shuler & Bear, 2006). Many studies have also described experience-dependent plasticity following perceptual learning in other modalities or following motor learning (Recanzone, Merzenich, Jenkins, *et al.*, 1992; Karni *et al.*, 1995; Wang *et al.*, 1995; Dahmen & King, 2007). For instance, repetitive tactile stimulation on the hand was shown to modify neural representations in primary somatosensory cortex (SI) of non-human primates. In one study, animals were trained to discriminate the temporal sequence of tactile bar stimuli that spanned three neighboring digits. Animals responded to two consecutive indentations of the multi-digit stimuli on the same location. The authors observed an expansion of the canonical excitatory receptive field (RF) of SI (area 3b), from single to multiple digits (Wang *et al.*, 1995). It was surmised that this training promoted synaptic integration of coincident inputs, which in turn caused RF enlargement (Clark *et al.*, 1988; Allard *et al.*, 1991; Wang *et al.*, 1995). These findings are significant because they indicate that RF structure of cell populations can conform to the statistical properties of an organism's environment. However, the perceptual implications of these anatomical changes and the rules that facilitate transfer of learning to other tactile abilities remain unclear.

It has been shown that tactile spatial acuity improves with passive experience of vibratory stimuli within a single experimental session (Godde *et al.*, 2000; Hodzic *et al.*, 2004; Kalisch *et al.*, 2007). However, this spatial acuity improvement can co-occur with impairments in discriminating vibratory stimuli (Hodzic *et al.*, 2004). This increase in spatial acuity is associated with increased representation of the passively stimulated digit (Pleger *et al.*, 2003; Hodzic *et al.*, 2004). However, many of these studies used two point discrimination to quantify changes in spatial acuity, which can lead to inaccurate measurements (Johnson & Phillips, 1981; Craig & Johnson, 2000; Tong *et al.*, 2013). In addition, successful replication of these results has been mixed (Gibson *et al.*, 2009).

Our study examined the specificity of tactile perceptual learning by testing whether perceptual abilities across multiple digits are modulated with training on an unrelated multi-digit task. Moreover, we assayed whether these perceptual learning effects modulate according to the stimulus features and/or experimental rules of the training regime. We used a tactile-one-back-task that closely mirrored that of Wang and colleagues (1995), which was shown to increase the size of RFs of somatosensory cells. This task required detection of two consecutive indentations of a horizontal bar stimulus that spanned two neighboring digits. Participants trained on this task daily for ten days, and after training sessions spatial and temporal discrimination thresholds were quantified on both hands; in a separate control group we only tracked these thresholds. In this manner we could describe the time course and trends of such changes and test if changes were specific to the trained hand or to trained subjects. We hypothesized that training on a task using multi-digit stimuli would enhance spatial discrimination across multiple digits, while at the same time lead to deficits on a single finger. For temporal discrimination, we reasoned that stimulus or procedural learning could guide transfer (Hawkey *et al.*, 2004; Ortiz & Wright, 2009, 2010). If stimulus learning,

or learning associated with specific features of a trained stimulus, guided generalization to other tactile abilities, a task which uses consistent synchronous multi-digit stimuli would promote integration across digits. This could therefore make tasks that required comparisons between digits more difficult. Alternatively, improvement discriminating the temporal order of multi digit stimuli could transfer to other tactile temporal tasks. If such procedural/task learning- that associated with response demands of a task- guided transfer, temporal discrimination of other tactile stimuli would be enhanced. Finally, we contended that changes in both spatial and temporal discrimination would be selective for the features (e.g. orientation) of the tactile stimuli experienced during the training regime.

GENERAL METHODS

Sequence of events: Training, Testing and Recovery Sessions

The study was conducted in ten sessions over a two-week period (excluding recovery tests). On the first day, we measured participants' perceptual thresholds on grating orientation and temporal acuity tasks in both hands. Participants then trained for nine days over a two week period on a multi-digit tactile one-back task on their right hand, similar to the non-human primate study by (Wang *et al.*, 1995). This "Tactile One-Back Training" (TOBT) took a half hour a day. This two-week time period was chosen as it produces changes in somatosensory responses in humans trained on the same multi-digit one-back task (Spengler *et al.*, 1997). At the end of each training session we measured participants' thresholds on the grating orientation task (GOT) on single and multiple digits, and temporal discrimination thresholds (TDTs) between two digits. The order of these acuity tests was randomized. We quantified all thresholds on either the trained and untrained hand in a separate session (Figure 1). These tests took an additional half hour per day. The GOT took approximately twenty minutes and temporal discrimination ten minutes. To assess hand specificity, we measured these thresholds on both hands but in the interest of time alternated which hand's thresholds were measured each day. That is, the subject would perform TOBT on their right hand and then we measured GOT thresholds and TDT on the right hand; the next day participants would again perform TOBT on their right hand but we would assess thresholds on the left hand. While we predicted that continuous performance on the GOT and TDT will induce their own perceptual learning effects that may modulate thresholds, we also predicted there would be *additional* learning effects, induced by TOBT, which would further modulate orientation and temporal perceptual thresholds. We predicted these would be specific to the stimulated hand and/or experimental parameters of TOBT. Therefore, we additionally compared threshold measures on the untrained hand to a small group of control participants who did not engage in the TOBT task, but whose grating orientation and temporal discrimination thresholds were measured over nine days. These data were compared with the same data from experimental subjects' untrained hands to assess what changes in thresholds were due to continuous exposure to the GOT and temporal acuity tests and what changes were related to TOBT.

Participants' grating orientation and temporal discrimination thresholds on both hands were retested after cession of TOBT to assay long-term perceptual effects of TOBT on tactile

spatial and temporal abilities. This recovery test occurred at least a month after the last day of TOBT.

Participants

Ten healthy human subjects gave written informed consent in compliance with policies of the Institutional Review Board for Human Use of the Johns Hopkins University and participated in the experiments. The participants were seven females (three males), nine right-hand dominant (one left handed, self-reported), and between 18–30 years old (median age was 20). Five additional participants were recruited to participate in the control protocol (two males, all right-hand dominant), ages 18–31, median age 20. Four (two male, all right handed) were tested for nine days in both the GOT and temporal acuity tests on their left hand, one subject was only tested on the GOT for nine days on their left hand. All testing procedures were performed in compliance with the policies and procedures of the Institutional Review Board for Human Use of the Johns Hopkins University. Participants were given a small monetary compensation at the end of each day.

Training Paradigm: Tactile One Back Training (TOBT)

Participants sat comfortably in a quiet room with their right hand supinated in a customized holder to prevent hand and finger movements. A black curtain blocked the view of the hand and tactile stimulator. On every trial, two horizontal bar stimuli (see “Mechanical stimulators” for details) that spanned the distal and proximal finger pads of D3 and D4 were indented on participants’ right hand to simultaneously contact the two digits. The bars were wedge-shaped to produce a smooth edge sensation. Indentation of the bars alternated between distal and proximal pads. After a random number of alternate stimulus indentations (between three and eight), two consecutive stimuli (target stimulus) were presented at the same location (Figure 1A). Participants were instructed to press a button with their left hand as quickly as possible in the event of a target stimulus, and withhold a response to all other stimuli. Response feedback, in the form of an auditory tone, was provided after every correct response only. After any overt response (correct or incorrect), the tactile stimuli would pause for 1 second to provide enough time for participants to adequately process the subsequent volley of stimuli. White noise was continuously presented to mask auditory cues from the motors. Participants performed three sets of 80 trial sequences (~500 stimuli) with a five-minute break in between each set. A small portion (5%) of tactile sequences was presented on only one finger to enhance the likelihood that participants attended to both fingers. Participants were instructed to ignore these trials and only respond to consecutive indentations spanning both fingers. The experimenter provided feedback of an incorrect response when participants responded to consecutive indentations on a single-digit. No participants responded during these trials after the first day of training. Participants experienced 240 tactile sequences, 228 target stimuli, and approximately 1500 total stimuli on each day.

On the first day of training the inter-stimulus interval (ISI), stimulus indentation level, and stimulus duration were adjusted to ensure that participants’ baseline performance was approximately 60%. This was done to ensure that task difficulty was equated across participants, and to enhance the likelihood of eliciting robust perceptual learning effects (see

Table 1 for a detailed description of the stimulus parameters). Stimulus ramp time was always 20 msec. After this point, stimulus parameters were kept constant to quantify improvement to the same set of stimuli throughout TOBT.

Behavioral performance on the TOBT was estimated using D-prime analyses. D-prime was calculated by taking the difference between the z-scores of the hit and false alarm rates during that day's performance. Hit rate was defined as the number of responses to a target stimulus divided by the total number of targets (228 targets a day; this was collapsed across all sequences and therefore the time between target stimuli was not considered for this analysis), and false alarm rate was defined as the number of responses to a non-target stimulus divided by the total number of non-target stimuli (i.e. the number of stimuli alternating between distal and proximal pads, ~1200 non target stimuli per day). In cases where hit rate was 1, this was transformed to 0.999. In cases where there were no false alarms, the false alarm rate was transformed to 0.001. Note that during TOBT, target position/sequence length was fully randomized within each training session. Correct responses at the longest sequences were considered hits, unlike in (Recanzone *et al.*, 1993). We found that subjects had more false alarms during sequences with longer alternations (false alarm rate averaged 10.29% for shortest sequences with 3–4 alternations, and 18.58% for longest sequences with 7–8 alternations), and more misses during shorter alternations (on average across the nine days of training, subjects missed 26.16% of shortest sequences and 18.95% of longest sequences). However, these differences across sequence length did not vary as a function of training day.

Grating Orientation Task (GOT)

We quantified participants' 75% threshold levels on the well-established grating orientation task (GOT)(Johnson & Phillips, 1981; Van Boven & Johnson, 1994; Craig & Johnson, 2000). Participants were presented with a series of eight square-wave gratings cut into rounded plastic domes (Ultem plastic) with equal ridge and gap widths (0.35, 0.5, 0.75, 1, 1.25, 1.5, 2, and 3mm, based on design by Stoelting Co., Wood Dale, IL). A dome was indented 2mm into the finger using a linear motor for 1500 msec. The domes were consistently placed 14mm from the end of the fingertip, thus stimulating the upper half of the distal finger pad. Gratings were presented “vertically” (along the long axis of the finger) or “horizontally” across the medial/lateral axis of the finger. Participants were instructed to judge the orientation of each stimulus and report, with a mouse button press using the unrestrained hand, which of the two orientations was perceived (left and right button push for horizontal and vertical, respectively).

The orientations were chosen randomly on every trial and each grating size was presented thirty times across randomized blocks. On the first day we tested participants on four grating sizes with widths ranging from 1.25 to 3mm. The following day, and on each subsequent day, we used three grating widths that encompassed the previous day's thresholds (four widths in a subset of participants). This was done to reduce the experimental testing time and to ensure threshold was accurately tracked over time. A grating dome covering one digit was presented to participants' right hand D3 or D4 (digits three and four, middle and ring digits, on the trained hand) and the left hand D2 or D3 (digits two and three, index and

middle digits, on untrained hand). Our goal was to contrast changes in thresholds on homologous and nonhomologous digits in the untrained hand. However, we observed that participants' baseline threshold on the right D4 and left D2 was significantly different as compared to other fingers (Post-hoc contrasts by Scheffe's, $F_{2,18} > 7.1$, $P < 0.05$). This is in line with previous studies that have demonstrated decreasing acuity from index to ring fingers (Sathian & Zangaladze, 1996; Grant *et al.*, 2006; Wong *et al.*, 2011). Therefore, to assay changes in GOT thresholds with similar baselines we analyzed data on D3 between both hands.

Multi-digit thresholds were quantified in a protocol where two domes of equal grating width and orientation were indented at the same time on two fingers (D3 and D4 on trained hand, and D2 and D3 on untrained hand). Participants were instructed to judge whether the grooves were horizontal or vertical across both fingers. We did not tell participants that the orientation was the same on both fingers, but asked that they attend to both fingers, in an attempt to create a task that required perception of stimuli across multiple digits. The trained and untrained hands were tested on alternate days, beginning with the right hand (i.e. the trained hand). This was done to reduce testing time. We determined participants' GOT threshold as the grating width that elicited correct responses on 75% of trials. Thresholds were estimated using all trials, and for each orientation condition by using performance on trials with horizontal and vertical stimuli separately. As the task is a two alternative forced-choice, and only two types of stimuli were presented (horizontal or vertical stimuli), modulations in orientation-specific thresholds can be influenced by changes in response bias. We unfortunately did not introduce catch trials with smooth dome stimuli, which would have accurately estimated subject bias throughout training.

Tactile Temporal Discrimination

We measured participants' temporal discrimination threshold (TDT) using two oriented bars on two adjacent distal fingertips (19 mm long, 300 μ m indentation, 200 msec duration, 20msec stimulus ramp time). The bars were wedge-shaped to produce a smooth edge sensation. Bars were either oriented horizontally across the fingertips (congruent orientation), or one bar was indented vertically while the other was indented horizontally (incongruent orientation). We quantified TDT on D3 and D4 of the right hand (trained digits) and D2 and D3 of the left hand (untrained digits). Baseline TDT was not statistically different on either hand. Participants indicated whether bars were indented at the same or different times (Lacruz *et al.*, 1991).

The stimulus onset asynchrony (SOA) between the two bars ranged between 0 and 100 msec in steps of 5 msec. We randomized which bar was indented first. Each SOA and orientation condition was presented six times, and this order was randomized. We estimated participants' TDT by determining the stimulus asynchrony that elicited 'same' responses on 50% of trials. As the psychometric curve in this task ranges from 0% (large SOAs, no stimuli classified as synchronous) to 100% (very small SOAs, all stimuli classified as synchronous), the 50% point represents threshold. TDT for both hands was calculated on the first day (baseline), and then we alternated which hand was tested, beginning with the right hand.

Recovery Tests

Participants were asked to return approximately one month after the last day of TOBT to reexamine their spatial and temporal thresholds (between 30 and 160 days post training). The goal was to assay long-term effects of TOBT on spatial and temporal thresholds.

Mechanical Stimulators

The stimulator used in TOBT and the temporal discrimination task consisted of four custom built linear motors (similar to those used in Killebrew et al., 2007) that have a nominal displacement of 2.9 mm. The four motors were positioned over the hand using four articulated tool holders (Noga Engineering Ltd. Shlomi 22832, Israel) mounted to four, two-axis micro-positioners (Newport Corp., California). Each motor was centered on the to-be stimulated finger pad using magnetic bases. Motors were controlled using a National Instruments data acquisition board (PCI-6229; National Instruments Corp., Austin, TX) and custom software. Motors moved with an on and off linear ramp duration of 20 msec.

The stimulator used in the GOT task consisted of a linear stage (Parker MX80L Miniature Stage; Parker Hannifin Corp, Rohnert Park, CA), mounted vertically and controlled with serial commands via a serial port interface and custom software. Two ARSAPE rotating stepper motors (AM 1020 series, Faulhaber Corp) were attached to the linear stage. The grating domes (Ultem plastic, design by Stoelting Co., Wood Dale, IL) were magnetically attached to the stepper motors with custom-designed holders, which allowed for a rapid replacement of stimuli between trial blocks. The linear motor moved with a ramp time of 300 msec over 8mm (indenting 2mm into the subjects' finger).

Data Analysis and Statistical Testing

We used repeated-measures analysis of variance (ANOVA) in SPSS v22 to statistically test for significant effects within the experimental group that had experienced TOBT and all results were corrected for sphericity using the Greenhouse-Geisser method. We performed Kolmogorov-Smirnov tests with Lilliefors significance correction on each cell (that is, for each condition and session, data from ten subjects), and found only two cells which were marginally significant: specifically, the fourth session vertical thresholds in the multi-digit GOT from the left hand (KS statistic, 0.27, $P=0.03$), and the second session congruent TDTs from the left hand (KS statistic= 0.27, $P=0.04$). For all others $P>0.05$. Given these marginal and very infrequent violations of normality in our dataset, we contend that our use of an ANOVA is justified. Post-hoc contrasts were corrected for multiple comparisons using Scheffe's method. Non-parametric statistics using Mann-Whitney U tests were used to test for effects between the small number of participants in the control group who were only tested on TDT and GOT (N=4 for TDT, 5 for GOT) and the untrained hand of TOBT participants (N=10).

RESULTS

Performance of the One-back Task

As expected, participants showed systematic increases in D-prime and corresponding decreases in reaction time (RT) throughout the training period (Figure 2). This was

confirmed using a one-way repeated measures ANOVA on D-prime with Day as the repeated factor ($F_{8, 72} = 11.26$, $P < 0.001$, $\eta_G^2 = 0.335$). We observed that D-prime rose from 1.97 to 3.33 across the training period. This effect was captured by a linearly increasing polynomial contrast ($F_{8, 72} = 41.75$, $P < 0.001$, $\eta_G^2 = 0.39$). A separate ANOVA on RT also revealed a significant effect of Day ($F_{8, 72} = 10.77$, $P = 0.001$, $\eta_G^2 = 0.20$), whereby RT decreased from 447 to 378 msec throughout training (linear polynomial contrast, $F_{8, 72} = 44.84$, $P < 0.001$, $\eta_G^2 = 0.20$).

We further quantified the day at which performance on the one-back task stabilized during training. We performed a series of ANOVAs where the earliest day of training was systematically removed from each test. For example, the first ANOVA was conducted using the full set of training days (9 days), while the second ANOVA was performed with the first day of training removed (8 days). This strategy was continued until the ANOVAs failed to show a significant effect. We found that ANOVAs on D-prime failed to show significant differences from the fourth day onward ($F_{5, 45} = 2.75$, $P = 0.09$) and RT failed to show significant differences from the fifth day onward ($F_{4, 36} = 2.82$, $P = 0.10$). This indicated performance during TOBT began to plateau between the fourth and fifth day of training.

Effects of TOBT on GOT Thresholds

After each TOBT session, we quantified participants' threshold on the GOT (Johnson & Phillips, 1981). We first examined subjects' overall GOT threshold, calculated using all trials. Figure 3 shows changes in this threshold across time in the single-digit (Figure 3A, left panel) and multi-digit condition (Figure 3B, left panel). The trained hand was tested every other day; therefore, five times throughout the experiment, but only the first four sessions were used in statistical tests to ensure a balanced design. However, for all conditions, there were no statistical differences between thresholds measured between the fourth and fifth session on the trained hand (paired t-test, $P > 0.05$). Thresholds were subtracted from those measured on the first experimental day prior to any TOBT. Absolute thresholds, with baseline included, are shown in Supplemental Figure 1. We asked if subjects' threshold changed in a hand and finger condition specific manner, hypothesizing that TOBT could enhance overall multi-digit GOT performance at the expense of single-digit GOT performance. We performed a $2 \times 2 \times 4$ within-subject ANOVA with factors of Number of Digits (Single vs. Multi), Hand (Trained vs. Untrained) and Session (One to Four). We observed a significant main effect of Session ($F_{3, 27} = 6.10$, $P = 0.005$, $\eta_G^2 = 0.03$), which was captured by a linear decreasing function as assessed by polynomial contrasts ($F_{3, 27} = 19.21$, $P = 0.002$, $\eta_G^2 = 0.03$). This is in line with previous studies, which show decreasing thresholds with continuous exposure to the GOT (Johnson & Phillips, 1981; Wong *et al.*, 2013). We did not observe other significant main effects or interactions, suggesting that TOBT does not impact overall GOT thresholds in hand or finger-condition specific manner.

However, we further predicted that the orientation of the stimuli used during TOBT would specifically impact GOT performance. We therefore examined 75% thresholds calculated separately for trials in which the GOT stimuli was oriented horizontally or vertically. Figure 3 (middle and right panels) shows changes in these thresholds across time in single-digit

(Figure 3A) and multi-digit (Figure 3B) conditions. We ran a four way $2 \times 2 \times 2 \times 4$ within-subject ANOVA with factors of Orientation (Horizontal vs. Vertical), Number of Digits (Single vs. Multi-digit), Hand (Trained vs. Untrained), and Training Session (One to Four). We again found a main effect of Training Session ($F_{3,27} = 10.43$, $P < 0.001$, $\eta_G^2 = 0.03$), which was captured by a linear decreasing function as assessed by polynomial contrasts ($F_{3,27} = 19.52$, $P = 0.002$, $\eta_G^2 = 0.03$). We also found a significant Orientation $\times$ Training Session interaction effect ($F_{3,27} = 7.05$, $P = 0.002$, $\eta_G^2 = 0.01$), with vertical threshold decreasing at a faster rate. This was captured by a linear trend (polynomial contrasts, $F_{3,27} = 14.28$, $P = 0.004$, $\eta_G^2 = 0.007$). The ANOVA also revealed a significant interaction between Number of Digits and Training Session ($F_{3,27} = 3.61$, $P = 0.04$, $\eta_G^2 = 0.01$). This was captured by a quadratic function (polynomial contrasts, $F_{3,27} = 11.76$, $P = 0.008$, $\eta_G^2 = 0.01$), with single-digit threshold increasing in the first sessions then decreasing, and multi-digit threshold decreasing then increasing. Finally, we found a significant four-way interaction between Orientation, Number of Digits, Hand, and Training Session ($F_{3,27} = 3.72$, $P = 0.04$, $\eta_G^2 = 0.008$). The effect underlying this four-way interaction is described in the following paragraph. No other significant effects were observed.

Our working hypothesis was that TOBT would lead to increasing single-digit GOT thresholds in an orientation and location specific manner. This was confirmed by our data, in that we observed a quadratic increase in horizontal single-digit threshold in the trained hand and a linear decrease in thresholds for the same stimulus but in the untrained hand (Figure 3A). We assessed the significance of this specific post-hoc effect using linear contrast analyses (Rosenthal & Rosnow, 1985). We assigned orthogonal and equally spaced weights to each data point, correcting for sphericity among participants. Based on observation of the data in Figure 3A (**middle panel**), we assigned linearly decreasing weights over four sessions to the untrained hand, weights [3, 1, -1, -3]. The trained hand's thresholds appeared to follow a trend whereby thresholds increased, decreased and stabilized, we therefore assigned weights [-2, 1, 0.5, 0.5]. This combination of trends was significant ($F_{3,27} = 16.47$, $P < 0.05$, $\eta_G^2 = 0.02$, corrected for sphericity and post-hoc statistical significance assessed using Scheffe's method). This indicated *specifically* that horizontal single digit orientation thresholds on the trained hand followed a quadratic trend, whereby it increased, decreased slightly, and plateaued. In contrast, the untrained hand's orientation thresholds on this exact same measure linearly decreased across sessions. While we observed that TOBT increased single-digit thresholds on a digit- and stimulus-specific manner, we failed to find the opposite effect in the multi-digit condition. Indeed, we observed that thresholds across multi-digits decreased across training sessions for all oriented stimuli in the trained and untrained hands (Figure 3B).

We further examined whether training effects observed in the untrained hand represented typical perceptual learning effects observed in GOT tasks (Johnson & Phillips, 1981; Wong *et al.*, 2013), as opposed to transfer effects across hands from TOBT. We compared the thresholds on the untrained hand with data from a separate set of participants who only experienced the spatial and temporal acuity tests but not TOBT (Figure 4). Independent samples Mann-Whitney U-tests revealed no significant differences between these two groups for each session and condition ($P > 0.05$ for each session), indicating that the effects

from the untrained hand represent typical learning effects produced by continuous experience of the GOT task.

We investigated the persistence of these training effects by reexamining participants' orientation-specific GOT thresholds over a month after their last day of TOBT. We performed a $2 \times 2 \times 2 \times 2$ ANOVA with factors of Orientation (Horizontal vs. Vertical), Number of Digits (Single vs. Multi-digit), Hand (Trained vs. Untrained), and Training Session (Last TOBT Session vs. Recovery Session). Because the time between testing varied among participants, we included the covariate of number of days between the recovery test and the last tested session. The ANCOVA did not reveal any significant effects, indicating no change in acuity during the recovery period (all main effects and interactions, $P > 0.05$).

Training-Specific Changes in Temporal Discrimination

We next examined whether TOBT modulated TDT across multiple digits (Figure 5). We hypothesized that TOBT would impair temporal discrimination of stimuli between the trained digits due to the continuous and synchronous stimulation experienced during the training period. This form of stimulation likely promotes integration across digits thus making tasks that required comparisons between digits more difficult. Alternatively, because TOBT relies on identifying a specific temporal pattern within a stream of stimulus indentations, abilities on other tactile temporal tasks may improve. We further examined whether changes in temporal acuity are selective to the stimulus orientation pattern used during training (i.e. two bars oriented horizontally). We therefore measured TDT in two conditions: one where the asynchronous bar stimuli was oriented congruently horizontally across the digits (as in TOBT) or where one bar was oriented vertically and the other horizontally (incongruent condition). We again subtracted subjects' baseline temporal acuity prior to TOBT (non-subtracted thresholds are shown in Supplemental Figure 2).

A three-way $2 \times 2 \times 4$ ANOVA with factors of Stimulus Congruency (Congruent vs. Incongruent), Hand (Trained vs. Untrained), and Session was computed to test for significant effects. Again, to maintain a balanced design, only the first four sessions on the trained hand were used. Similar to above, no significant differences were observed in congruent or incongruent TDT on the trained hand between the fourth and fifth sessions (paired t-test, $P > 0.05$). The ANOVA revealed a main effect of Session ($F_{3,27} = 5.81$, $P = 0.01$, $\eta_G^2 = 0.04$) driven by decreasing thresholds throughout training, which was captured by a linear polynomial contrast ($F_{3,27} = 20.15$, $P = 0.002$, $\eta_G^2 = 0.02$). In addition, we found a significant Session $\times$ Hand interaction ($F_{3,27} = 3.82$, $P = 0.04$, $\eta_G^2 = 0.04$). Polynomial contrasts analysis revealed that this interaction was best explained by fitting a quadratic trend to the trained hand's data using the orthogonal weights [2 -1 -1 0]. These weights indicate the trained hand's threshold decreased, plateaued, and then slightly increased over the tested sessions. This trend and these weights were significant ($F_{3,27} = 16.05$, $P < 0.05$, $\eta_G^2 = 0.04$, corrected for sphericity and post-hoc statistical significance assessed using Scheffe's method). We assayed whether the untrained hand represented typical changes in TDT over time by comparing these data with those from a separate control group (Figure 6). The untrained hand and control subjects were not significantly different on any sessions

(Independent samples Mann-Whitney U test, $P > 0.05$ for each session). Therefore, improvements in temporal acuity are specific to the hand that experienced TOBT.

We measured intra-digit temporal acuity a month after TOBT. We computed a $2 \times 2 \times 2$ ANCOVA with factors Stimulus Congruency (Congruent vs. Incongruent), Hand (Trained vs. Untrained), and Session (Last TOBT Session vs. Recovery Session). We included the number of days during the recovery period as a covariate. The ANCOVA failed to reveal any significant effects, suggesting no changes in temporal discrimination abilities after cession of training (all main effects and interactions, $P > 0.05$).

DISCUSSION

We assessed whether training on a task that promotes multi-digit RF expansion would enhance discrimination of stimuli spanning multiple digits. In addition, we tested whether enhancements in multi-digit discrimination would come at the expense of discrimination at the single-digit level. We examined how such training impacted temporal judgements across digits, testing if stimulus properties or training procedures specify generalization. Finally, we investigated whether these effects are feature specific with regard to the trained stimulus.

GOT and temporal acuity tasks were performed daily, and we predicted they would indeed induce their own learning effects. However, we hypothesized TOBT would cause additional changes to spatial and temporal thresholds. Supporting our hypothesis, as participants trained on the multi-digit TOBT, we found location and orientation-specific changes in temporal and spatial discrimination thresholds. We contend that features of TOBT, involving temporal sequence discrimination of horizontal multi-digit stimuli, predict these changes. Specifically, we observed that participants' temporal discrimination threshold across the trained digits decreased during training while orientation thresholds of horizontal single-digit grating stimuli increased during the training period. As the GOT is a two alternative-forced choice design, and we did not introduce catch trials of smooth stimuli or in oblique orientations, we cannot remove participant bias from our orientation-specific threshold calculations. Therefore it is unclear if these results are at least partially due to changing bias with training, whereby subjects increased their likelihood of indicating grating stimuli was "vertical" on the trained digit. These trends were in contrast to stable TDTs and decreasing horizontal thresholds in the GOT on the untrained hand. Importantly, thresholds on the untrained hand were similar to thresholds in a control group which did not experience TOBT. We did not observe, as we had originally predicted, decreasing thresholds while subjects discriminated multi-digit grating stimuli on the hand that had experienced TOBT. These data suggest that experience-dependent plasticity following perceptual learning can both enhance and interfere with tactile perception in a predictable manner.

Features of TOBT Predict Changes in Grating Orientation Thresholds

We found that participants' performance during TOBT improved throughout the training period. This improvement plateaued around five days of training (Figure 2). In support of our hypothesis, we observed that single-digit thresholds on the trained hand increased and plateaued. This pattern was specific to the orientation of the stimulus experienced during training (i.e. horizontal). We contend that these modulations in threshold were largely a

result of TOBT on the trained hand, as participants' untrained hand showed clear linearly decreasing thresholds and closely mirrored a separate group of participants who did not experience TOBT.

Contrary to our hypothesis, we found no difference between trained and untrained hands on multi-digit GOT, particularly for the horizontal orientation, as tested using our experimental design (Figure 3B). It may have been that hand-specific improvements were masked by daily GOT performance. Alternatively, it may have been because we used nonhomologous digits to measure GOT thresholds on the two tested hands (D3 and D4 on the trained hand and D2 and D3 on the untrained hand), or a result of intersubject variability in performing the task, which used two gratings oriented in the same direction. Some subjects may have attended to both digits to perform the task as instructed, while others attended to one digit.

Mechanisms Explaining Changes in GOT Thresholds Due to Experience-Dependent Plasticity Following Perceptual Learning

In the field of visual perceptual learning, feature (e.g. orientation) and location (e.g. retinal location or eye tested) specificity has often been cited as evidence for plasticity changes in primary sensory cortex (Fiorentini & Berardi, 1980; Ball & Sekuler, 1982; Karni & Sagi, 1991; Crist *et al.*, 1997; Fahle, 1997, 2004). Studies have observed changes in neural responses in primary visual cortex (V1) as a result of visual experience, for example non classical RF modulation with the presence of contextual stimuli, orientation specificity, sustained responses to stimuli which predict reward at a temporal interval (Crist *et al.*, 2001; Schoups *et al.*, 2001; Li *et al.*, 2004; Shuler & Bear, 2006). However, few, if any, have observed changes in V1 RF properties like size or orientation preference (Crist *et al.*, 2001; Ghose *et al.*, 2002). On the other hand, SI cortical map plasticity and alterations in SI RF properties have been described following learning on a tactile task using a consistent tactile stimulation regime (Jenkins *et al.*, 1990; Recanzone, Merzenich, & Schreiner, 1992; Recanzone, Merzenich, Jenkins, *et al.*, 1992; Blake *et al.*, 2002), but the consequences on perception have not been described. Our study provides insight onto the functional implications of RF expansion promoted by multi-digit task training.

Cells with an excitatory RF confined to one finger are likely to be functionally connected to those with input from adjacent fingers via horizontal (Négyessy *et al.*, 2013; Wang *et al.*, 2013) or divergent ascending input (Garraghty & Sur, 1990; Rausell *et al.*, 1998). Several studies in area 3b have shown modulatory effects on the classical single-digit RF by stimulation of adjacent digits (Friedman *et al.*, 2008; Reed *et al.*, 2010; Thakur *et al.*, 2012). These connections between digits in area 3b could be modified by continuous engagement during TOBT (Wang *et al.*, 1995). Interference in discriminating single-digit grating stimuli could be possible if TOBT expands horizontally tuned cells' single-digit RFs into excitatory multi-digit RFs in 3b. This would reduce the cortical representation of a single digit, potentially making judgments, particularly judgments of horizontal stimuli, less accurate on a single-digit. As subjects were forced to choose between a "horizontal" and "vertical" response during the GOT, this may explain why vertical bias could have increased on the trained digit. In addition, some studies (Wheat & Goodwin, 2000; Vega-Bermudez & Johnson, 2004; Gibson & Craig, 2005) have observed tactile anisotropy with enhanced

discrimination of vertical stimuli; this may be related to increased skin compliance along dermal ridges (Vega-Bermudez & Johnson, 2004) and increased responses of slowly adapting peripheral afferents to stimuli oriented along dermal ridges (Phillips & Johnson, 1981; Wheat & Goodwin, 2000). Anisotropy for radial stimuli has also been observed in the visual system (Sasaki *et al.*, 2006). Therefore in the face of perceptual uncertainty during horizontal trials, subjects may be biased to choose the more easily discriminable orientation. Though the precise link between cortical maps and spatial tactile perception is still unclear, several studies have noted changes in 2-point spatial discrimination which correlate to the degree of SI and SII (secondary somatosensory cortex) cortical reorganization following coactivation (Pleger *et al.*, 2003), TMS (Tegenthoff *et al.*, 2005), and chronic pain syndrome (Pleger *et al.*, 2006).

We should note that the trained hand's single-digit horizontal thresholds did not become worse than baseline; therefore any decrements in discrimination abilities are only relative to the untrained hand. One can therefore think of TOBT as interfering with typical perceptual learning on the GOT. We also note that our measures cannot eliminate subject bias. Nonetheless, we contend that our findings are representative of a mechanism by which perceptual learning interferes with discrimination of tactile features on a different, but related, task. This occurs in a feature and location specific manner. Additionally, our data support the hypothesis that conscious processing of sensory features is not necessary to induce perceptual learning changes (Watanabe *et al.*, 2001; Seitz & Watanabe, 2003, 2009; Seitz *et al.*, 2009), particularly if suppression of sensory stimuli is unnecessary or reinforcement is correlated with a particular stimulus feature (Sasaki *et al.*, 2010). That is, even though performance during TOBT was not reliant on judging the orientation of the stimulus, the effect on GOT thresholds was orientation-specific.

Enhancements in Temporal Acuity

We found that participants' TDT across trained fingers decreased, plateaued, and then slightly increased. This was in contrast to the untrained hand and control subjects whose TDT was stable over several sessions. One hypothesis, assuming stimulus learning following TOBT (Ortiz & Wright, 2009) was that the formation of multi-digit representations would make comparisons between fingers more difficult. However, this hypothesis assumes temporal discrimination would rely on a comparison between cell populations conveying the timing of stimuli on a single-digit, and that expansion of RFs would impair such judgments. This need not be the case, as computational studies have demonstrated large RFs could convey information about timing of stimuli (Foffani *et al.*, 2008), and SI RF expansion occurs in concert as animals learn to discriminate the timing of noncoincident stimuli across digits (Blake *et al.*, 2005). We do not know the neural mechanisms or cortical regions serving such temporal judgments, though it has been suggested that parietal cortex is involved in comparing the timing of two stimuli (Aghdaee *et al.*, 2014). Alternatively, it is likely that the general rules of TOBT, which require the identification of a stimulus' temporal pattern on finger locations, transfer to the temporal discrimination task and explain enhancements in temporal processing of other tactile stimuli. Such generalization is likely a result of "procedural" or "cognitive" learning during TOBT, which has been observed and described in other modalities (Hawkey *et al.*, 2004; Ortiz & Wright, 2009; Wright *et al.*,

2010). We found that enhanced temporal acuity was not specific to the orientation of the trained stimulus, as TDT decreased even when participants compared the timing between incongruent oriented bars. This is in contrast to orientation-specific increases in GOT thresholds, suggesting that temporal and spatial tactile abilities are affected differentially by TOBT. In addition, the temporal time courses described by our linear trend analysis find differences between changes in TDT and GOT thresholds. The return of trained hand TDTs to levels similar to baseline and the untrained hand near the end of TOBT may be explained by a renormalization process during TOBT (observed in auditory cortices, see Reed *et al.*, 2011). Perhaps neural substrates underlying TDT are only altered as subjects become proficient at the one-back task in the first few days of TOBT.

Recovery and Clinical Implications

While we did not see tactile single-digit horizontal GOT thresholds significantly change during the recovery period, we did observe shifts that suggest that perceptual abilities renormalize after a long period without training. That is, horizontal GOT thresholds on the trained digit become more similar to the untrained digit following recovery (Figure 3A, **middle** panel). This is in contrast to perceptual effects of passive tactile co-activation, which are completely extinguished after 24 hours (Godde *et al.*, 2000; Hodzic *et al.*, 2004). It may be that active participation and continuous TOBT over many days explains enduring effects, as well as mixed effects of tactile coactivation on tactile spatial acuity (Gibson *et al.*, 2009). Certainly, better understanding of this renormalization process would be of great importance to clinical populations. In particular, our findings are relevant to patients with focal dystonia for whom experience-dependent plasticity is maladaptive and related to pronounced motor and sensory deficits. Investigators have implicated somatosensory cortex RF expansion in the development of focal hand dystonia (Byl *et al.*, 1997; Blake *et al.*, 2002). It has been suggested that this RF expansion is related to patients' abnormal tactile spatial acuity (Bara-Jimenez *et al.*, 2000), and undoing these multi-digit representations may be related to symptom relief (Candia *et al.*, 2003). However, it is still unclear exactly the relationship between specific types of tactile input, sensorimotor hand skill development, and these findings. It is clear that those interested in learning and rehabilitation will need to better understand how training on one task might transfer to perceptual abilities and tasks. For example, it has been suggested that popular online "brain training" tasks have little bearing on other cognitive skills (Owen *et al.*, 2010). Our results suggest that one should consider interference as well as enhancement to other perceptual abilities as a result of continuous training on sensory tasks.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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ABBREVIATIONS

D2	Digit two, index finger
D3	Digit three, middle finger
D4	Digit four, ring finger
GOT	Grating orientation task
RF	Receptive field
SI	Primary somatosensory cortex
TOBT	Tactile one-back training
TDI	Temporal discrimination threshold

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Experimental methods

Figure 1. Experimental methods

(A) Tactile one-back training (TOBT). Participants experienced horizontal bars that spanned the right middle and ring fingers (D3 and D4). One bar was located distally (near the fingertip) and the other proximally (closer to the palm of the hand). Participants were asked to indicate with a button press when they felt a bar consecutively indent at the same location. They were given feedback if they correctly responded in the designated hit window. Stimulus parameters are indicated, and were adjusted on the first day of training to ensure participants were performing around 60% correct. **(B)** Testing phase. Participants' intra and inter-digit discrimination thresholds on the GOT (right panel) and inter-digit temporal discrimination thresholds (left panel) were measured prior to any training on both hands (baseline). Each day, following TOBT, we measured one hand's thresholds on these tests, alternating the hand tested.

Figure 2. Performance during tactile one back training (TOBT)

Participants' (N=10) D-prime (black line, $Z(\text{hit rate}) - Z(\text{false alarm rate})$) is indicated on the left y-axis, and reaction time for correct trials (grey dashed line) on the right y-axis. All error bars are standard error of the mean (SEM), calculated by removing between-participant variability considering this is a within-participant design (see Cousineau, 2005 for a description).

A. The effect of TOBT on single-digit GOT thresholds

B. The effect of TOBT on multi-digit GOT thresholds

Figure 3. The effect of TOBT on thresholds in the grating orientation task (GOT)

(A) Changes in D3 single-digit grating orientation threshold (relative to baseline) on the right trained (black) and left untrained (grey dashed) hands. Session 1 is day 1 of TOBT for the trained hand and day 2 for the untrained hand, session 2 is day 3 for the trained hand and day 4 for the untrained hand. The untrained hand was tested five times but only the first four sessions were used in the ANOVA. **Left panel: changes in threshold (at 75% correct) using all trials, Middle: changes in threshold on horizontal-only trials, Right: changes on vertical-only trials.** The trained hand was tested over five sessions, however for statistical purposes (to ensure a balanced design) only the first four sessions were analyzed. Threshold was re-tested at least one month after session of TOBT (recovery). Error bars are $\pm$ within-participant S.E.M. (B) Changes in multi-digit threshold on the trained digits (black, right D3 and D4) and untrained hand and digits (grey dashed, left D2 and D3). **Left panel: changes in overall GOT threshold. Middle: threshold on horizontal-only trials. Right: Threshold on vertical only trials.** Error bars are $\pm$ within-participant S.E.M.

A. Single digit GOT thresholds in the untrained hand versus control subjects

B. Multi-digit GOT thresholds in the untrained hand versus control subjects

Figure 4. GOT thresholds on the untrained hand and in control participants

(A) Changes in D3 single-digit grating orientation threshold (relative to baseline) on the untrained hands of participants who experienced TOBT (N=10, grey dashed) and control participants who did not experience TOBT (N=5, black). **Left: 75% Threshold using all trials. Middle:** changes in threshold on horizontal-only trials, **Right:** threshold on vertical-only trials. The untrained hand was tested over only four sessions and we tested control participants on the GOT over nine days. (B) Changes in multi-digit threshold on the untrained hand and digits (left D2 and D3, N=10 grey dashed) and on the same hand/digits for control participants (N=5, black). **Left: Threshold on all trials Middle:** threshold on horizontal-only trials. **Right:** Threshold on vertical only trials. Error bars are $\pm$ between-group S.E.M.

Figure 5. The effect of TOBT on temporal acuity

(**A**) Participants' change in temporal discrimination threshold (TDT) relative to baseline, across the trained digits (right D3 and D4) and the untrained hand/digits (left D2 and D3). Bars were oriented congruently horizontally (as in TOBT) across digits. Error bars are $\pm$ within-participant S.E.M. (**B**) Participants' change in TDT relative to baseline on the trained and untrained hands. In this protocol, one bar was oriented vertically (medio-laterally) across the finger. Error bars are $\pm$ within-participant S.E.M.

Figure 6. Temporal acuity on the untrained hand and in control participants

(A) Participants' change in temporal discrimination threshold (TDT) relative to baseline, across the untrained hand/digits (N=10, left D2 and D3, grey dashed) versus control participants (N=4, black) who had not experienced TOBT. Bars were oriented congruently horizontally (as in TOBT) across digits. (B) Participants' change in temporal discrimination threshold (TDT) relative to baseline, across the untrained hand/digits (left D2 and D3, grey dashed) versus control participants (black). In this protocol, one bar was oriented vertically (medio-laterally) across the finger. Error bars are $\pm$ between-groups S.E.M.

Table 1
Stimulus parameters of tactile one-back training (TOBT)

Number of subjects who experienced specific stimuli parameters, adjusted on the first day of training and kept constant through the remainder of the experiment.

Stimulus parameter				
ISI (msec)	350–450 (n = 7)	400–500 (n = 2)	450–550 (n = 1)	
Indentation (μm)	125 (n = 1)	150 (n = 1)	200 (n = 4)	300 (n = 4)
Duration(msec)	50 (n = 3)	80 (n = 7)		