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Magnetic stimulation of visual cortex impairs perceptual learning

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ABSTRACT

The ability to learn and process visual stimuli more efficiently is important for survival. Previous neuroimaging studies have shown that perceptual learning on a shape identification task differently modulates activity in both frontal-parietal cortical regions and visual cortex (Sigman et al., 2005; Lewis et al., 2009). Specifically, fronto-parietal regions (i.e. intra parietal sulcus, pIPS) became less activated for trained as compared to untrained stimuli, while visual regions (i.e. V2d/V3 and LO) exhibited higher activation for familiar shape. Here, after the intensive training, we employed transcranial magnetic stimulation over both visual occipital and parietal regions, previously shown to be modulated, to investigate their causal role in learning the shape identification task. We report that interference with V2d/V3 and LO increased reaction times to learned stimuli as compared to pIPS and Sham control condition. Moreover, the impairment observed after stimulation over the two visual regions was positive correlated. These results strongly support the causal role of the visual network in the control of the perceptual learning.

1. Introduction

Observers can voluntarily attend to a location in the visual field, and subsequent stimuli at that location will be recognized more accurately and rapidly (Posner, 1980). Furthermore, visual perception can be improved through specific training, a phenomenon called Visual Perceptual Learning (VPL) (Gibson, 1963). VPL is one of the strongest examples of plasticity in the adult brain and a core feature of visual cognition. VPL might depend on attention (Ahissar and Hochstein, 1993) and allows for more efficient responses to environmental stimuli.

Despite several decades of investigations, neuronal mechanisms of VPL remain debated (Gilbert et al., 2001; Sasaki et al., 2010; Shibata et al., 2014). Neurophysiologic and neuroimaging studies indicated that VPL induces changes of neural activity in visual cortex (Crist et al., 2001; Schoups et al., 2001; Schwartz et al., 2002; Furmanski et al., 2004) and in higher-order brain regions (Chowdhury and DeAngelis, 2008; Law and Gold, 2009) involved in the control of spatial attention (Sigman et al., 2005; Lewis et al., 2009), as well as in their interaction (Liu et al., 2010; Lewis et al., 2009).

It has been suggested that VPL shifts the critical locus of processing for learned stimuli from higher-order control regions, early on during training, to visual cortex after learning is completed. For example, in human observers, intensive training on a shape orientation identification task causes a shift in the pattern of activation, measured with blood oxygenation level dependent (BOLD) signals in functional magnetic resonance imaging (fMRI), between frontal-parietal regions (so-called dorsal attention network, DAN) and occipital visual regions (Sigman et al., 2005; Lewis et al., 2009). Specifically, in our study (Lewis et al., 2009), frontal and parietal regions (e.g. posterior intra-parietal sulcus, pIPS) known to be involved in the control of visuospatial attention were more strongly active for novel (untrained) stimuli, and attenuated their response for familiar (trained) stimuli. In contrast, occipital visual regions responded more strongly to trained than untrained stimuli. Moreover, learning-induced modulation of visual cortex activity was topographically selective. In fact, since the task required observers to discriminate stimuli at a peripheral location in the left lower quadrant, corresponding activity modulation was recorded in right dorsal visual cortex. In particular, higher activation was observed in both right V2d/V3 and lateral occipital region (LO; Lewis et al., 2009). Finally, response modulations were behaviorally relevant: subjects with higher sensitivity to trained shapes showed stronger modulation in the trained quadrant of visual cortex. Overall these findings support the hypothesis that whereas higher-order frontal and parietal regions are more important early

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on in training presumably for directing visuospatial attention and selecting unfamiliar stimuli, attention control becomes less important later on as 'templates' of learned shapes are consolidated in visual cortex.

While the above studies have provided invaluable information on the neural mechanisms of VPL, there is actually scarce direct evidence that the learning specific visual regions (i.e. V2d/V3 and LO) are actually mediating perceptual learning. Here we used repetitive TMS (rTMS) in healthy volunteers to test with a causal approach hypotheses that are based on our fMRI findings (i.e. correlative), and specifically the crucial role of visual cortices in shape identification task. Using the same visual paradigm of our mentioned studies (Lewis et al., 2009; Baldassarre et al., 2012), after the intensive training, rTMS was employed to interfere with the activity in right V2d/V3, LO, or pIPS. If VPL is completed and the template of learned shape is formed in the corresponding (i.e. right) visual regions, then we predict that the inactivation of parietal cortex (i.e. pIPS) will not affect the behavioral performance. On the contrary, we expect impairment in detecting familiar shapes after inactivation of both visual cortices (i.e. V2d/V3 and LO). Furthermore, since our previous neuroimaging experiments showed a similar learning-related fMRI modulation for V2d/V3 and LO, we predict a similar impairment in such visual regions.

2. Materials and methods

2.1 Subjects and stimuli

16 right-handed volunteers (age range: 20–30 yrs. old; 8 females) participated in this experiment. A preliminary self-reported questionnaire assessed that they did not present previous psychiatric or neurological history. Participants gave written consent according to the Institutional Review Board and Ethics Committee of the University of Chieti. The computer monitor was placed in front of them at a distance of about 60 cm.

Subjects were trained with daily sessions to attend to the lower left visual quadrant and find the target shape among the distracters while maintaining central fixation. The stimulus array comprised 12 Ts arranged in an annulus of low eccentricity (i.e. 5° radius) and was displayed across the 4 visual quadrants. Of note, with such low eccentricity in our previous study (Lewis et al., 2009) we did not observed significant eye movements. On each trial subjects fixated a central spot for 200 ms (fixation), after which the target shape (an inverted T) was presented at the center of the screen for 2000 ms (target presentation); finally, an array of 12 stimuli, differently oriented Ts (distracters) with or without an inverted T (target), was briefly flashed for 150 ms (array presentation). The target shape appeared randomly in 1 of 3 locations in the left lower (trained) visual quadrant, and never in the three untrained-quadrants. The target shape appeared randomly in 1 of 3 locations in the left lower (trained) visual quadrant, and never in the other three untrained quadrants. Subjects attended to the lower left visual quadrant and indicated the presence or absence of the target shape visual quadrant by pressing a left/right mouse button with their right hand (Fig. 1a). Each block consisted of 45 trials, 36 (80%) that contained the target and 9 (20%) that did not. Training lasted one week, and an average of 100 practice blocks were necessary to reach a threshold of 80% accuracy in at least 12 consecutive blocks of trials (see Fig. 1b for a representative psychophysical curve). Of note, the accuracy of each block was weighted with the rate of false positive (Sigman and Gilbert, 2000; Sigman et al., 2005; Lewis et al., 2009).

When subjects reached criterion, they were asked to perform three blocks of the same task during each TMS condition (i.e. V2d/V3, LO, pIPS, and Sham). Presentation timing was triggered by the TMS train (see below), and the four TMS conditions were run in a counterbalanced order across subjects, who were instructed to respond as accurately and quickly as possible. Reaction times and the accuracy of the response were recorded for behavioral analyzes. Notably, none of the subjects reported discomfort or pain during each stimulation site.

2.2 Procedures for rTMS and identification of target scalp regions

TMS stimulation was delivered through a focal, figure eight coil, connected with a standard Mag-Stim Rapid 2 stimulator (maximum output 2.2 T). Individual resting excitability threshold for right motor cortex stimulation was preliminarily determined following standardized procedure (Rossini et al., 1994). The rTMS train (i.e. 3 pulses) was delivered simultaneously to the central spot ~2 s before the stimuli array with the following parameters: 150 ms duration, 20-Hz frequency, and intensity set at 100% of the individual motor threshold. The parameters are consistent with published safety guidelines for TMS stimulation (Rossi et al., 2009). Of note, previous studies have shown that such stimulation has effect for at least 2 s, thus affecting target processing (Capotosto et al., 2009, 2012a, 2012b).

All participants performed three active rTMS (i.e. V2d/V3, LO, and pIPS) and one inactive TMS (i.e. Sham) conditions corresponding to each stimulation site, applied in different blocks and counterbalanced across subjects. In the "Sham" condition, a pseudo

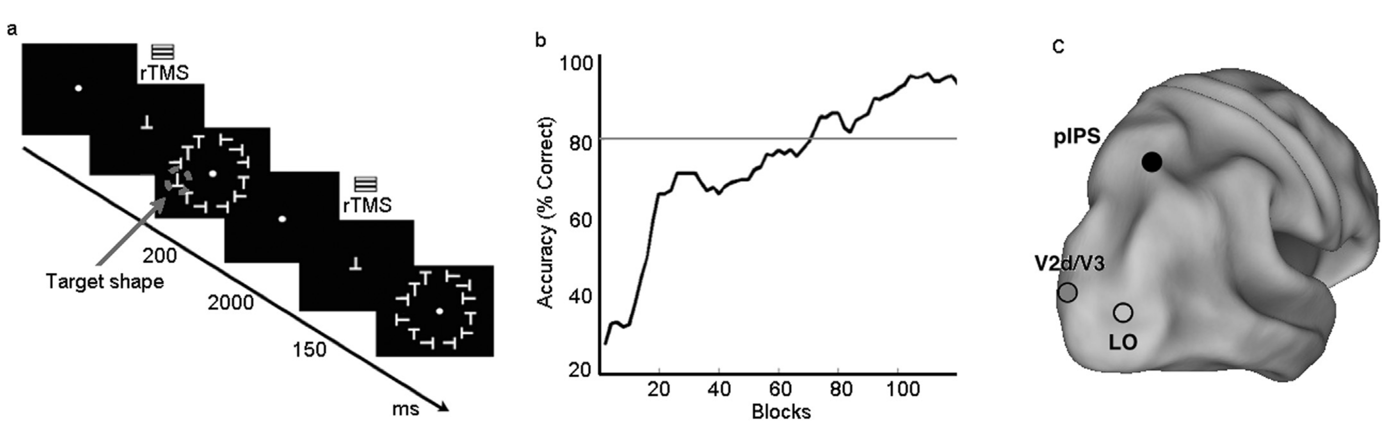

Fig. 1. a) Example of the display sequence in the perceptual learning task. b) Example of a single subject's learning curve. Each block contains 45 trials. The gray line indicates a learning threshold of 80% accuracy in 10 consecutive trial blocks. c) Inflated view of left hemisphere atlas brain with regions of attention and visual networks as in previous work of Lewis et al. (2009). Regions with coordinates are stimulated with rTMS in this experiment and are as follows: right LO: 38, −87, 7 (x, y, z); right V2d/V3: 17, −97, 16; right pIPS: 32, −60, 51.