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Coordinated neural, behavioral, and phenomenological changes in perceptual plasticity through overtraining of synesthetic associations

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ABSTRACT

Synesthesia is associated with additional perceptual experiences, which are automatically and consistently triggered by specific inducing stimuli. Synesthesia is also accompanied by more general sensory and cortical changes, including enhanced modality-specific cortical excitability. Extensive cognitive training has been shown to generate synesthesia-like phenomenology but whether these experiences are accompanied by neurophysiological changes characteristic of synesthesia remains unknown. Addressing this question provides a unique opportunity to elucidate the neural basis of perceptual plasticity relevant to conscious experiences. Here we investigate whether extensive training of letter-color associations leads not only to synesthetic experiences, but also to changes in cortical excitability. We confirm that overtraining synesthetic associations results in synesthetic phenomenology. Stroop tasks further reveal synesthesia-like performance following training. Electroencephalography and transcranial magnetic stimulation show, respectively, enhanced visual evoked potentials (in response to untrained patterns) and lower phosphene thresholds, demonstrating specific cortical changes. An active (using letter-symbol training) and a passive control confirmed these results were due to letter-color training and not simply to repeated testing. Summarizing, we demonstrate specific cortical changes, following training-induced acquisition of synesthetic phenomenology that are characteristic of genuine synesthesia. Collectively, our data reveal dramatic plasticity in human visual perception, expressed through a coordinated set of behavioral, neurophysiological, and phenomenological changes.

1. Introduction

Synesthesia is an ontogenetic variant of healthy human development characterized by specific additional experiences in response to normal sensory input. For instance, in grapheme-color synesthesia the letter “A” printed in black (inducer) may elicit a red color experience (concurrent). The concurrent experience is automatically triggered and is not under voluntary control. Although, the specific associations are inter-individually idiosyncratic but intra-individually highly consistent (Ward, 2013), large-scale studies also show reliable consistencies across individuals (e.g., Simner et al., 2005; Witthoft et al., 2015). Furthermore, grapheme-color synesthesia is associated with a specific neural profile (e.g., Brang et al., 2008; Brang et al., 2011; Esterman et al., 2006; Hubbard et al., 2005; Muggleton et al., 2007; Rouw and Scholte, 2007, 2010), which includes increased cortical excitability (Terhune et al., 2011) and increased visual perceptual processing (Barnett et al., 2008b). The associative nature of synesthesia motivated early attempts to induce synesthesia by means of associative learning (Howells, 1944; Kelly, 1934). However, it was not until very recently that the acquisition of synesthetic phenomenology in response to graphemes using associative training was successful (Bor et al., 2014). This recent finding, together with established neural characteristics of genuine synesthesia, provides a unique opportunity to elucidate the neural basis of perceptual plasticity relevant to conscious experiences. We therefore set out to examine whether training-induced synesthesia-like phenomenology is accompanied by neural changes characteristic of genuine synesthetes.

Genuine grapheme-color synesthesia (henceforth synesthesia if not otherwise specified), is accompanied by enhanced modality-specific cortical excitability. For example, application of transcranial magnetic stimulation (TMS) to primary visual cortex reveals that grapheme-color synesthetes had significantly lower phosphene thresholds in

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comparison to non-synesthetes, whereas there was no group difference when motor thresholds were tested by TMS applied to the motor cortex (Terhune et al., 2011; cf. also, Terhune et al., 2015a, 2015b). Demonstrating enhanced sensory-perceptual processing, electroencephalographic (EEG) measurements showed that grapheme-color synesthetes exhibit an enhanced response for specific visual evoked potential components (VEPs; measured over occipital and parieto-occipital areas), compared to non-synesthetes while they viewed high contrast checkerboard patterns; note that these checkerboard patterns did not themselves elicit synesthetic experiences (Barnett et al., 2008b).

Behaviorally, synesthesia is characterized by the consistency and the automaticity of synesthetic associations. The 'gold standard' in diagnosing synesthesia is the test of consistency (Baron-Cohen et al., 1993; Eagleman et al., 2007). Participants are presented with potential synesthetic inducers (e.g., letters and numbers) several times in random order and are required to select the corresponding concurrent experience (e.g., color). An individual-specific measure of consistency can be derived from the average distance in color-space across repeated selections of the same inducer. While synesthetes can rely on their perceptual experiences to perform this task, non-synesthetes have to rely on memory. Thus, synesthetes are far more consistent in this task than non-synesthetes. The automaticity of synesthetic associations is assessed with adapted Stroop-type tasks (Stroop, 1935). Grapheme-color synesthetes are faster at making a decision about a congruently colored letter in comparison to an incongruently colored letter. This would not be the case if the associations had to be triggered voluntarily (e.g., Dixon et al., 2004; Rothen et al., 2013b; Ward et al., 2007).

Early attempts to induce synesthetic phenomenology focused on sound-color synesthesia (Howells, 1944; Kelly, 1934). These historic studies used associative training procedures over several weeks, including a minimum of 2000 stimuli in a subset of participants (Kelly, 1934) or approximately 30,000 stimuli (Howells, 1944). The results were mixed. Only the latter study appeared partly successful in inducing synesthetic phenomenology (Howells, 1944). No (recorded) further attempts were made to induce synesthetic phenomenology until more than half a century later (e.g., Meier and Rothen, 2009; Rothen et al., 2011; Colizoli et al., 2012). These more recent studies focused on grapheme-color synesthesia, which is currently the best studied form of synesthesia (see Rothen and Meier, 2014 for a review). Most involved daily training sessions of a few minutes, over periods lasting from a few days to maximally 4 weeks. Training sessions typically consisted of a single task which was based on explicit or implicit associative learning procedures, during which participants were presented with "congruent" (to-be-learnt grapheme-color associations) and "incongruent" stimuli (not-to-be-learnt grapheme-color associations). The ratio of congruent to incongruent trials ranged from 1:0 to 1:8, across different studies. While most studies found behavioral evidence that associations became automatic over the course of the training (especially those with fewer incongruent trials), none of them found evidence for synesthetic phenomenology. For instance, after training, participants were faster at making a color decision about a grapheme when it was presented in a congruent, in comparison to an incongruent, color (i.e., synesthetic Stroop effect; Meier and Rothen, 2009), but did not report altered phenomenology (e.g., additional color experiences).

Recently, Bor et al. (2014) demonstrated that it is possible for non-synesthetes to acquire synesthetic color phenomenology in response to letters. In comparison to previous training studies, this study employed an extensive battery of adaptive cognitive training tasks and only reinforced congruent letter color pairings. The daily training lasted approximately 60 min per day for 9 weeks (5 days per week). After five weeks the participants passed the synesthetic consistency test, showed a synesthetic Stroop effect, and – critically – reported synesthetic phenomenology. However, potential neurophysiological changes associated with these effects were not measured in this study.

To examine the neural basis of perceptual plasticity relevant to conscious experience, we investigated the phenomenological (subjective reports), behavioral (consistency and automaticity) and neural (cortical excitability) consequences of extensive training of synesthetic associations (letter-color associations). In order to control for changes that may arise purely because of extensive training, rather than because of the specific letter-color associations we employed, we also tested an active control group. This active control underwent an alternative training regime that employed analogous letter-symbol pairings, but which did not involve color associations. We also tested a passive control group, which underwent repeated testing but no associative training between the testing sessions.

We hypothesized that for the experimental (letter-color) group, post-training compared to pre-training testing would reveal reports of synesthetic phenomenology, increased grapheme-color consistency, enhanced automaticity for the trained associations (i.e., synesthetic Stroop effect), and enhanced cortical excitability (i.e., reduced phosphene thresholds to TMS and enhanced VEPs to checkerboard patterns). By contrast, these changes were not expected for the passive control group. For the active control group, who were trained on letter-symbol associations, we expected to find enhanced automaticity for the trained associations, but crucially no changes in color-related perceptual phenomenology and thus no changes in cortical excitability.

2. Materials and methods

Participants were only allowed to take part in the study if they did not report any instances of synesthesia during a recruitment interview and remained naïve as to the purpose of the study throughout the experiment. Experiments 1 and 3 consisted of a training paradigm, and a testing battery repeated before and after training; Experiment 2 consisted of repeated testing only. The testing battery consisted of TMS- and EEG-based tests for visual cortical excitability (Figs. 1A and 2A-B) and behavioral tests for consistency of letter-color associations (Fig. 3A) and automaticity of letter-color (Exp. 1 and 2) or letter-symbol (Exp. 3) associations (Fig. 4A). The testing session after the training further included a semi-structured interview for assessing perceptual phenomenology during exposure to individual letters of the alphabet. The battery was conducted before and after a five week training period (Exp. 1 and 3) or a five week training-free interval (Exp. 2). The training was conducted 5 days per week for 5 weeks, with each training session lasting approximately 60 min per session. The training was conducted to consolidate 13 specific letter-color associations (Exp. 1; cf. Bor et al., 2014) or to consolidate 13 specific letter-symbol associations (Exp. 3). Experiments 1, 2, 3 were designed and conducted consecutively. Therefore, pre-and post-training analyses were conducted separately for each experiment prior to a collective analysis encompassing all experiments. Experiments were undertaken with the understanding and written consent of each participant.

2.1. Sample size determination

We conducted a-priori power analyses for the neurophysiological parts of the study (i.e., TMS and EEG), because these were the novel and central aspects of present study. A-priori power was estimated based on the effect sizes of Terhune et al. (2011) for the TMS part and Barnett et al. (2008a) for the EEG part, corresponding to a power of 99% with $N = 6$ for the TMS part and a power of 95% with $N = 18$ in the predicted direction for the EEG part. The final N was further based on practical aspects: the study had to be conducted during term-time while the participating students were present on campus. Another crucial factor was how many participants could be tested in the relevant labs (especially EEG and TMS lab) during pre- and post-testing in order that the whole study would still fit into one term at the University of Sussex. Moreover, the number of students who were willing to participate and who fulfilled the inclusion criteria (i.e., no synesthetic experiences prior to the study) was another factor.