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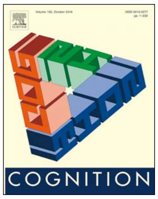

Original Articles

Unconscious decisional learning improves unconscious information processing

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ABSTRACT

The idea that unconscious input can result in long-term learning or task improvement has been debated for decades, yet there is still little evidence to suggest that learning outside of awareness can produce meaningful changes to decision-making. Here we trained participants using noisy motion stimuli, which require the gradual accumulation of information until a decision can be reached. These stimuli were suppressed from conscious awareness by simultaneously presenting a dynamic dichoptic mask. We show that a short period of training on either a partially or fully suppressed motion stimulus resulted in improved accuracy when tested on a partially suppressed motion stimulus traveling in the orthogonal direction. We found this improvement occurred even when performance on the training task was at chance. Performance gains generalized across motion directions, suggesting that the improvement was the result of changes to the decisional mechanisms rather than perceptual. Interestingly, unconscious learning had a stronger effect on unconscious, compared to conscious decisional accumulation. We further show that a conscious coherent percept is necessary to reap the benefits of unconscious learning. Together, these data suggest that unconscious decisional processing can be improved via training.

1. Introduction

The world around us is continuously broadcasting a mass of sensory information – yet only a fraction of it reaches our conscious experience. While the remaining information is lost to consciousness, it is widely believed that it can nonetheless affect our behaviour (Ansorge, Kunde, & Kiefer, 2014; Pessiglione & Lebreton, 2014; Van den Bussche, Van den Noortgate, & Reynvoet, 2009; van Gaal, Lamme, Fahrenfort, & Ridderinkhof, 2011; Zedelius et al., 2014). For example, we have previously shown that information can be accumulated outside of awareness and used to improve decision accuracy in a random dot kinematogram task (Lufityanto, Donkin, & Pearson, 2016; Vlassova, Donkin, & Pearson, 2014). However, this accumulation occurred at a much slower rate outside of awareness. Other studies looking at perceptual processing outside of awareness have found similar deficits of unconscious processing compared to conscious perception (e.g. de Lange, van Gaal, Lamme, & Dehaene, 2011; Del Cul, Baillet, & Dehaene, 2007; Greenwald, Draine, & Abrams, 1996). We therefore wondered whether people could learn to better utilise information outside of awareness.

Performance on a perceptual task can be improved with practice (Epstein, 1967; Gibson, 1969). These improvements tend to be feature-specific; perceptual learning effects tend to not transfer across stimulus features such as motion direction, orientation and location (Ball & Sekuler, 1987; Crist, Kapadia, Westheimer, & Gilbert, 1997; Fiorentini & Berardi, 1980; Saffell & Matthews, 2003). Perceptual learning has therefore been associated with changes in the primary visual cortex and higher-level visual areas. However, learning associated changes can also occur beyond visual areas. Several studies have looked at sensory decision making specifically, and found that performance improvement on a motion-discrimination task was associated with changes in LIP, but not MT (Law & Gold, 2008). Since LIP activity reflects decision processing and not simply low-level motion processing (Gold & Shadlen, 2000, 2001, 2007; Mazurek, Ditterich, & Shadlen, 2003; Roitman & Shadlen, 2002; Shadlen & Newsome, 2001), this suggests that learning on a perceptual decision task is associated with improvements to the decision system, and is not strictly limited to improvements to visual processing.

A prevailing view of perceptual learning is that conscious effort and focused attention must be directed at a stimulus or feature for perceptual learning to occur, as learning effects are not found for unattended task-irrelevant stimuli (Ahissar, 2001; Huang, Lu, Tjan, Zhou, & Liu, 2007; Li, Piëch, & Gilbert, 2004; Schoups, Vogels, Qian, & Orban, 2001; Shiu & Pashler, 1992). However, several studies have challenged this notion by demonstrating that task-irrelevant perceptual learning can occur for weak and unattended stimuli following repeated exposure (Seitz & Watanabe, 2003; Watanabe, Náñez, & Sasaki, 2001).

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Importantly, these studies found that learning did not generalise to different motion directions, indicating that the inattentive learning occurred at lower levels of visual processing. Several studies have also demonstrated perceptual learning for unconscious, masked stimuli (Schwiedrzik, Singer, & Melloni, 2009, 2011). However, here too, learning effects were shown to be limited to lower levels of the visual hierarchy, as performance improvement did not transfer to untrained spatial locations. Moreover, improvements in task performance were found to be accompanied by increases in subjective visibility of the stimuli. It therefore remains unclear whether unconscious processing itself can be improved with training, or whether some level of conscious awareness is a necessary precondition for learning to occur. Together, these studies suggest that the visual system can adapt to ecologically valuable information, even when the observer does not attend to - or is not aware of - the source of the information. However, it remains unclear whether such learning can occur for higher level decisional processing in the absence of conscious awareness.

Here, we investigated whether training on a motion stimulus suppressed from conscious awareness could result in improved accumulation of unconsciously presented evidence, resulting in higher decision accuracy. To preview, we show that a short period of training on either a partially or fully suppressed motion stimulus results in improved accuracy when tested on a partially suppressed motion stimulus moving in an orthogonal direction. We found this improvement occurred even when performance on the training task was at chance. Performance gains generalised across motion directions, suggesting that the improvement was the result of changes to decisional mechanisms rather than low-level perceptual mechanisms. Moreover, we show that unconscious learning had a stronger effect on unconscious decisional accumulation than on conscious information accumulation. We further show that a coherent conscious percept is necessary to reap the benefits of unconscious learning.

2. Methods

2.1. Participants

Fifteen experimentally naïve participants were recruited for each experiment (Experiment 1: 6 male, 18–27 years of age; Experiment 2: 6 male, 18–24 years of age; Experiment 3: 8 male, 18–29 years of age; Experiment 4: 6 male, 19–30 years of age), for a total of 60 subjects across all 4 studies. All participants had normal or corrected-to-normal vision and provided informed written consent. All experiments were approved by the UNSW Human Research Ethics Advisory Panel. Participants received course credit in exchange for their participation.

2.2. Apparatus

Participants were seated on a height-adjustable chair at a distance of 42-cm from a 20-in. SONY Multiscan G520 CRT monitor, with a resolution 1280 × 960 and a refresh rate of 75-Hz. Participants' heads were stabilized by a chin and headrest housing a mirror stereoscope apparatus adjusted for each observer. This apparatus uses circular mirrors to display images separately to each eye, which overlap one another to form a single image when viewed binocularly. Stimuli were presented using Psychtoolbox Version 3 (Brainard, 1997) for MATLAB on a Macintosh MacPro machine running Mac OS X.

2.3. Stimuli

The motion stimuli utilized in this study were dynamic random dot kinematogram (RDK) displays, commonly used in research in perceptual decision making (Smith & Ratcliff, 2004). The RDK consisted of 100 grey dots (10.1 cd/m^2), each a 1 × 1 pixel square, moving at a speed of 6.1° per second on a black background. On each trial the direction of the motion was randomly chosen from a pool of an equal number of leftward and rightward directions. Three uncorrelated sequences of dot movement were generated and frames were interleaved so that each frame was correlated only with a frame that was either three frames backwards or forwards (Roitman & Shadlen, 2002; Shadlen & Newsome, 2001).

Dots were displayed within an invisible 8.2° diameter circular aperture, with a central 0.7° diameter fixation point. Participants were instructed to maintain fixation on this point throughout the experiments in order to facilitate fusion. On average, dot density was 1.9 dots/deg^2, and in order to conserve dot density, any of the signal dots that moved along a trajectory that would place them outside of the circular aperture were wrapped around to appear from the opposite side. This ensured that motion energy was uniform across the different levels of motion coherence.

We used the dynamic suppression mask originally developed in Vlassova et al. (2014) to suppress conscious awareness of the motion stimulus. The mask consisted of 250 green dots (59.5 cd/m^2) each a 1 × 1 pixel. Dots were displayed within an invisible 9.8° diameter circular aperture around a central 0.7° diameter fixation point, with an average dot density of 3.3 dots/deg^2. The dots moved concentrically around the central fixation point (clockwise) at a rate of 1.67 revolutions per second. This mask configuration has been previously shown to consistently and effectively suppress a dot-motion stimulus from conscious awareness for durations up to 500 ms (Vlassova et al., 2014).

2.4. Procedure

In our first experiment, we investigated whether training on a suppressed motion stimulus could produce improvements in decisional accuracy. We presented a dynamic mask concurrently with a coherent (10%, 30% or 60%) grey dot-motion stimulus for 400-ms, followed by 400-ms of visible random motion (see Fig. 1 for test/training structure and Fig. 2A for a detailed timeline). On each trial, participants were asked to decide the overall direction (left or right) of the dot-motion stimulus. Participants were then asked to report whether they saw any part of the suppressed stimulus using the keyboard (“Press ‘1!’ if you saw any grey dots while the green dots were also on the screen, Press

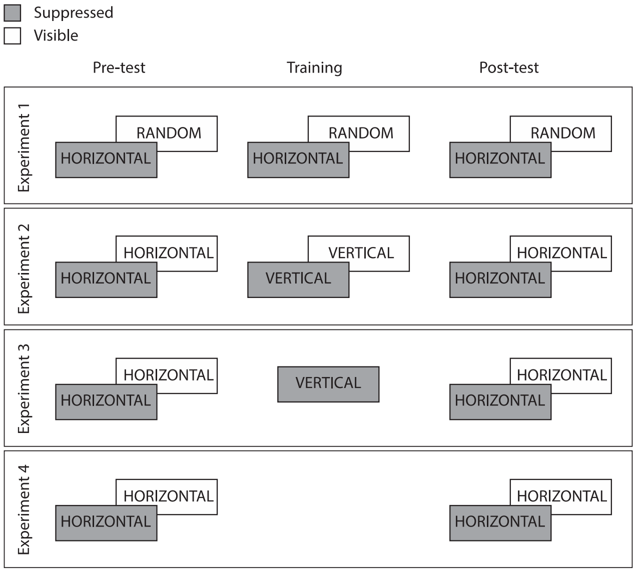

Fig. 1. Schematic outlining the test and training structure of Experiments 1–4. The grey shaded boxes represent the suppressed portion of each trial, while the white boxes represent the visible portion. In Experiments 2–4, the test trials were the same, and only the training blocks were manipulated. Note also that the direction of motion was counterbalanced across participants (i.e. half of the participants trained on vertical and were tested on horizontal motion, and half were trained on horizontal and tested on vertical motion.