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The Müller–Lyer illusion seen by the brain: An event-related brain potentials study

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Abstract

In two experiments, event-related brain potentials (ERPs) were used to examine the neural correlates of a visual illusion effect in Müller–Lyer illusion tasks (illusion stimuli) and baseline tasks (no-illusion stimuli). The behavioral data showed that the illusion stimuli indeed yielded an illusion effect. Scalp ERP analysis revealed its neurophysiological substrate: the Müller–Lyer illusion tasks (Illusion tasks 1–3) elicited a more negative ERP deflection than did the baseline tasks about 400 ms after onset of the stimuli. Dipole source analysis of the difference wave (Illusion task 2–Baseline task 1) and the original waveforms of the different conditions (Illusion tasks 2 and 3 and Baseline task 2) indicated that the anterior cingulate cortex (ACC)/superior frontal cortex may contribute to the illusion effect, possibly in relation to high-level cognitive control. The results indicated that apparent distortions of the Müller–Lyer illusion might be influenced by top-down control.

Keywords: The Müller–Lyer illusion; Anterior cingulate cortex (ACC); Event-related potentials (ERPs)

1. Introduction

Optical-geometric illusions are context-induced subjective distortions of visual features, such as the length, size, shape, and direction of one or more of the elements within a visual array. One of the best-known and most extensively investigated geometrical illusions, the Müller–Lyer configuration, in which the length of a line is overestimated when its ends are terminated with arrows pointing inward (> <) and is underestimated when its ends are terminated with arrows pointing outward (< >), has fascinated researchers for over 100 years (Valentin and Gregory, 1999).

It is well known that the Müller–Lyer illusion results from interactions between two arrowheads and the line between them. Different explanations for the occurrence of the Müller–Lyer illusion have been advanced. For example, depth theories (misapplied size constancy theory) suggested that an object's apparent size was determined by certain depth cues which operate neural size-scaling mechanisms directly in some cases (Gregory, 1963; Fisher, 1967; Valentin and Gregory, 1999). According to Gregory, subjective depth impression is automatically induced by the Müller–Lyer figures. That is, the target line with inward-pointing brackets looks longer because we perceive the line as more distant, and vice versa. Assimilation theory (averaging theories) held that the arrowheads interfere with the perceptual system for measuring span of the horizontals, and therefore observers confuse or average the distance between the arrowhead tips (Erlebacher and Sekuler, 1969; Pressey, 1970). Pressey (1970) thought that the length of the central shaft is misperceived because the visual system cannot successfully isolate parts from wholes. In this scenario, the central shaft of the figure with arrows pointing inward is seen as longer because the stimulus is, in its totality, longer. Confusion theory (displaced vertex theory) suggested that the perceptual system miscalculates the location of the arrowhead vertex, displacing it toward the concave side (Chiang, 1968). In particular, our judgment of the position of each end of the shafts is influenced by the arrows around it. Inward-pointing arrowheads shift the apparent shaft end-point outwards relative to the true end-point. Outward-pointing arrowheads cause the apparent end-point to move inwards. Since we misjudge where the ends of the shafts are, we tend to overestimate the length of

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the shaft in the inward-pointing arrows figure, and underestimate its length in the outward-pointing arrows figure.

As for now, the Müller–Lyer illusion has been measured as a function of the shaft length, the gap between the shaft and the apices of the wings, the wing tilt angle and the wing length (Bertulis and Bulatov, 2001). However, a satisfactory and reliable model for the Müller–Lyer illusion has not been found yet. Recently, Howe and Purves (2005) provided a new hypothesis that the standard Müller–Lyer effect and its variants are a result of the fundamentally probabilistic strategy of visual processing that contends with inverse optics problem. They said that ''the identical shafts or intervals in Müller–Lyer stimuli appear different in length because the probability distributions of the real-world sources of the lines or intervals, given the contexts provided by the arrowheads or arrow tails, are in fact different'' (Howe and Purves, 2005).

Recently, developed brain imaging techniques such as functional magnetic resonance imaging (fMRI) and positron emission tomography (PET) have made it possible for us to precisely record the brain activity associated with many cognitive processes, including visual illusion effects. For example, Lebedev et al. (2001) demonstrated that prefrontal cortex activity can reflect the perception of a visual illusion. In their study, they found a population of cells in the prefrontal cortex that reflected a monkey's report of displacement (even when wrong) in the displacement illusion task using single cell spikes. Weidner and Fink (2006) investigated the neural mechanisms underlying the Müller–Lyer illusion using fMRI and found that the neural processes associated with the strength of the illusion were located bilaterally in the lateral occipital cortex (LOC) as well as the right superior parietal cortex (SPC). They speculated that illusory line-length information and cognitive set interact in the right intraparietal sulcus (IPS), which suggests that the strength of the illusion selectively alters higher cognitive processes involved in visuospatial judgments. As early as 2004, Predebon (2004) examined the effect of selective spatial attention on the magnitudes of the Müller–Lyer illusion and claimed attentional modulation of illusion magnitudes implicates high-level or cognitive factors in the formation of the illusion.

Although previous studies using functional magnetic resonance imaging had obtained some important and interested findings about the neural mechanism of visual illusion, there are still controversies about the cognitive mechanisms of visual illusion, and the time course of cortical activation cannot be studied with precision. It is known that ERPs may provide a means to evaluate timing of cognitive processes prior to a response. In the ERP technique, recordings are made of the electrical activity of the brain that is time locked to the presentation of an external stimulus. Thus, ERP data allow for more precise statements about the time course of activation during different stages of processing (e.g., low-level visual perception or high-level cognitive control) of the Müller–Lyer illusion. In the present study, the purpose of the study was to investigate spatiotemporal patterns of brain activation during the Müller–Lyer illusion using high-density (64-channel) ERP recordings and dipole source analysis. First, we wanted to find out which modulations of the ERPs are consistently associated with visual illusion effects by comparing the Müller–Lyer illusion task with the baseline task. Based on previous work and different theories (Lebedev et al., 2001; Predebon, 2004; Weidner and Fink, 2006; Howe and Purves, 2005), we hypothesized that apparent distortions of geometric illusions (the Müller–Lyer illusion) may not depend on basic perceptual principles (low-level visual perception) but be influenced by top-down control. In the present study, the baseline tasks (including the Baseline tasks 1 and 2, see Figs. 1 and 4) which were not involved in context-induced subjective distortions of visual features might have the similar visual processing with the Müller–Lyer illusion tasks, such as primary visual cortex and saccadic eye movement (frontal eye field). Therefore, it could be a better way to investigate spatiotemporal pattern of brain in perception of the Müller–Lyer illusion figure by analyzing the difference wave (illusion tasks–baseline task) and test different theories of visual illusion. Second, high-density ERP recordings and dipole source analysis were used to obtain critical spatiotemporal information for analyzing the functional neuroanatomy of the cognitive processes involved in the illusion, which could validate results of previous studies and allow a more thorough investigation of the brain mechanisms involved. According to our hypothesis, we predicted that the prefrontal cortex or the anterior cingulate cortex might be involved in high-level cognitive control during visual illusions. To the best of our knowledge, this work is the first ERP study to investigate the electrophysiological correlates of the Müller–Lyer illusion.

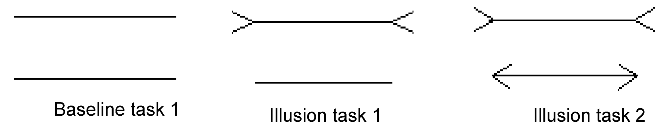

Fig. 1. Stimulus including Baseline task 1, Illusion task 1 (the shaft with inward-pointing arrowheads is seen as longer subjectively) and Illusion task 2 (the shaft with inward-pointing arrowheads is seen as longer subjectively) in Experiment 1.

2. Experiment 1

In this experiment, individuals performed the Müller–Lyer illusion tasks (Illusion tasks 1 and 2, see Fig. 1) and one baseline task (Baseline task 1, see Fig. 1). Subjects were instructed to judge whether a set of presented arrow shafts were the same length. Data from three conditions were considered in the analyses (Illusion task 1 [illusion response]; Illusion task 2 [illusion response]; and Baseline task 1 [correct response]). Electrophysiological data for correct judgment of shaft length in illusion trials were not considered, as there were not a sufficient number of these responses to obtain stable estimates of the ERPs. The experiment was designed to investigate the neural correlates of illusion effects elicited by the Müller–Lyer stimulus. Based on previous work, we expected visual processing of the illusion tasks and the baseline task to activate the occipital extrastriate cortex (Weidner and Fink, 2006; Ffytche and Zeki, 1996) but high-level cognitive processing of