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Neuropsychologia 44 (2006) 101–109

NEUROPSYCHOLOGIA

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Visual mental imagery during caloric vestibular stimulation

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Received 28 September 2004; received in revised form 17 March 2005; accepted 12 April 2005
Available online 17 May 2005

Abstract

We investigated high-resolution mental imagery and mental rotation, while the participants received caloric vestibular stimulation. High-resolution visual mental imagery tasks have been shown to activate early visual cortex, which is deactivated by vestibular input. Thus, we predicted that vestibular stimulation would disrupt high-resolution mental imagery; this prediction was confirmed. In addition, mental rotation tasks have been shown to activate posterior parietal cortex, which is also engaged in the processing of vestibular stimulation. As predicted, we also found that mental rotation is impaired during vestibular stimulation. In contrast, such stimulation did not affect performance of a low-imagery control task. These data document previously unsuspected interactions between the vestibular system and the high-level visual system.

Keywords: High-level vision; Occipital cortex; Rotation; Semicircular canal; Sensory interaction

1. Introduction

The vestibular system plays a fundamental role in human spatial orientation. For example, it activates the vestibulo-spinal reflexes needed to control posture and affects gaze via the vestibulo-ocular reflex (VOR). The VOR connects the vestibular end-organ to the eye muscles in such a way that moving the head in one direction induces a compensatory eye movement in the opposite direction. This reflex helps stabilize the image of the world on the retina, when we move our heads. Furthermore, vestibular information is used, when we perceive the orientation of objects (e.g., with respect to gravity, Mittelstaedt, 1983), and it continuously updates the internal representation of space (e.g., Berthoz, Israel, Georges-Francois, Grasso, & Tsuzuku, 1995).

Numerous neuroimaging studies of the human vestibular system have now been reported, some of which have shown that early visual cortex is deactivated during vestibular stimulation (Bense, Stephan, Yousry, Brandt, & Dieterich, 2001; Deutschländer et al., 2002; Wenzel et al., 1996). This result is consistent with findings reported by Tiecks, Planck, Haberl, & Brandt (1996), who, using Doppler sonography, found that vestibular stimulation reduces blood flow in the posterior cerebral artery, which supplies the occipital cortex. Brandt, Bartenstein, Janek, & Dieterich (1998) and Brandt et al. (2002) interpreted this finding as reflecting an inter-sensory interaction that helps prevent sensory conflicts (e.g., eliminates distracting visual information caused by retinal slip during vestibular stimulation). In fact, researchers have also documented the complementary pattern, a deactivation of vestibular areas during visually induced self-motion (Brandt et al., 1998; Deutschländer et al., 2004) and visual fixation (Naito et al., 2003). These findings are consistent with those from psychophysical studies that show increased thresholds for detecting body acceleration during visually induced body motion (Probst, Straube, & Bles, 1985).

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doi:10.1016/j.neuropsychologia.2005.04.005

The present study took advantage of the finding that vestibular stimulation deactivates the occipital cortex in order to study visual mental imagery. Many neuroimaging studies of visual mental imagery have shown that early visual areas, including area 17, are activated, when people form detailed, high-resolution visual mental images (for review, see Kosslyn & Thompson, 2003). However, neuroimaging is essentially a correlational technique. Although one transcranial magnetic stimulation study did show that deactivating medial occipital cortex impairs imagery (Kosslyn et al., 1999), this finding does not demonstrate deactivation via natural mechanisms of sensory integration and would, therefore, be more compelling if buttressed by convergent evidence using natural stimulation and entirely different techniques (cf. Pylyshyn, 2002, 2003). If early visual areas are in fact deactivated during vestibular stimulation, and high-resolution visual imagery relies on such areas, then we expect to find impaired performance in high-resolution imagery during such stimulation.

Moreover, we had a second reason for studying mental imagery during vestibular stimulation. Neuroimaging studies have revealed activation in parietal cortex during certain imagery tasks, particularly those involving mental rotation (Alivisatos & Petrides, 1997; Cohen et al., 1996; Kosslyn, DiGirolamo, Thompson, & Alpert, 1998; Richter et al., 2000). It is noteworthy that some of the areas found to be engaged in mental rotation tasks are also activated, when people perceive rotation during vestibular stimulation (e.g., the intra-parietal sulcus; Lobel, Kleine, Bihan, Leroy-Willig, & Berthoz, 1998; Lobel et al., 1999). Therefore, it is likely that such processing may be affected by vestibular stimulation. However, based on previous research, it is possible that simultaneous vestibular stimulation might not interfere, but rather could act to facilitate mental rotation. This alternative is supported by the report that mental imagery deficits following hemispatial neglect can be temporarily attenuated by vestibular stimulation (Rode & Perenin, 1994; Rode, Perenin, & Boisson, 1995). This finding suggests that vestibular information is important in constructing a representation of space, and hence vestibular stimulation conceivably could facilitate spatial imagery tasks.

Thus, our goal was to investigate the mechanisms shared by visual mental imagery and vestibular processes. We elicited a relatively constant vestibular response, while participants performed either a high-resolution mental imagery task, a mental rotation task, or a control task that did not require imagery, but instead required participants to evaluate statements about abstract entities. We did not expect vestibular stimulation to affect performance of the control task. In this study, we employed caloric stimulation to elicit vestibular stimulation. Caloric stimulation occurs, when a cold or warm temperature is applied to the outer ear canal, which in turn induces a thermoconvection within the fluid of the horizontal semicircular canal (Barany, 1906; Formby & Robinson, 2000). This stimulates the horizontal semicircular canal of the vestibular system as if the head were actually rotating.

2. Methods

2.1. Participants

Eight volunteers participated (five males and three females, ages 24–42 years) in two separate sessions. They received monetary compensation. Each participant was tested clinically and was verified to have normal vestibular and oculo-motor functions. None of the participants reported any history of vestibular problems or disease. This study was approved by the Institutional Review Boards at the Massachusetts Eye and Ear Infimary and Harvard University.

2.2. Tasks

2.2.1. High-resolution mental imagery

The participants began by memorizing 40 line drawings of common objects prior to the task (e.g., a grasshopper, a castle or a wrench). These pictures were taken from the standardized set developed by Snodgrass and Vanderwart (1980). The participants were instructed to memorize the objects so that they could later generate vivid mental images of the pictures, the same size as the original with all features. Neuroimaging revealed that early visual areas 17/18 typically are activated, when people visualize these objects (Ganis, Thompson, & Kosslyn, 2004; Kosslyn, Thompson, Kim, & Alpert, 1995). During the learning phase, each object was presented separately on a computer screen and the participants had as much time as they needed to memorize it. Once, they felt that they had memorized the object, they pushed a button and the object disappeared. They then formed the mental image of the object they just saw. When the participants had formed the mental image as accurately as possible, they pushed a button and the object reappeared on the screen. They checked whether their image matched the original, visualized again, and corrected the image if necessary. This procedure was repeated twice for each of the 40 pictures. It took the participants roughly 30 min to complete the learning phase.

During the experiment proper, the participants listened to the names of the objects they studied. As soon as they heard an object's name, they visualized the appropriate object as vividly as possible and retained this image until they heard a cue that indicated a specific judgment. The judgment cues were presented 2 s after they heard the name of the object. These questions directed the participants to "look" for one of four features on the image. After the learning phase, the participants were familiarized with the four different judgments: (1) *Higher than wide*: for this judgment, the participants considered the relative width of the imagined object from its leftmost point to its rightmost point (in a straight line), then compared that distance to that from the topmost extreme to the bottommost extreme (again in a straight line). If the distance from top to bottom was greater than the distance from left to right, they were asked to push the Yes-button on a hand-held device. Otherwise, they pushed the No-button. (2) *Center higher*: for this judgment, the participants considered