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Research Report

Illusion-related brain activations: A new virtual reality mirror box system for use during functional magnetic resonance imaging

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ABSTRACT

Extended viewing of movements of one's intact limb in a mirror as well as motor imagery have been shown to decrease pain in persons with phantom limb pain or complex regional pain syndrome and to increase the movement ability in hemiparesis following stroke. In addition, mirrored movements differentially activate sensorimotor cortex in amputees with and without phantom limb pain. However, using a so-called mirror box has technical limitations, some of which can be overcome by virtual reality applications. We developed a virtual reality mirror box application and evaluated its comparability to a classical mirror box setup. We applied both paradigms to 20 healthy controls and analyzed vividness and authenticity of the illusion as well as brain activation patterns. In both conditions, subjects reported similar intensities for the sensation that movements of the virtual left hand felt as if they were executed by their own left hand. We found activation in the primary sensorimotor cortex contralateral to the actual movement, with stronger activation for the virtual reality 'mirror box' compared to the classical mirror box condition, as well as activation in the primary sensorimotor cortex contralateral to the mirrored/virtual movement. We conclude that a virtual reality application of the mirror box is viable and that it might be useful for future research.

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1. Introduction

Phantom limb pain (PLP) is a common experience affecting 50–80% of all persons after amputation of a limb (Nikolajsen et al., 2006) and is accompanied by changes in the primary somatosensory cortex (S1) (Flor et al., 1995). Mirror training has been shown to reduce PLP (Chan et al., 2007) and reverses cortical reorganizational changes related to PLP (Flor et al., 2006; Foell et al., 2014). After its original proposal as a method to alleviate phantom limb pain, mirror training is now also used for the treatment of complex regional pain syndrome (McCabe et al., 2003) and symptoms after stroke (Sathian et al., 2000), among others. The concept behind mirror training is to provide the subjects with a visual image of their affected limb using a so-called mirror box, which could, for example, relieve painful involuntary 'clenching spasms' (Ramachandran et al., 1995). When conflicting information is presented to vision and another sense (including touch), vision tends to take precedence (Halligan et al., 1996; Moseley et al., 2008; Rock and Victor, 1964). Additionally, vision provides better spatial and temporal resolution of a stimulus than somatosensation, leading to the primacy of visual over somatosensory cues in multisensory integration (Ernst and Banks, 2002).

Using a mirror box has technical and conceptual limitations, which can partially be overcome by using a computer-generated virtual environment ('virtual reality mirror box' (VRMB)) instead of an actual real-life mirror. First and foremost, there are fewer degrees of freedom for movements in a classical mirror box (CMB) compared with a VRMB. For example, in the CMB, the intact and the mirrored limb are always seen as moving in unison, which goes against the natural use of the limbs, especially in case of the legs. With a VRMB, the inclusion of a time delay for the moved virtual limb is possible, yielding alternating limb movements. For use during functional magnetic resonance imaging (fMRI), which is usually done in a lying position, the placement of the arm in the CMB is also highly unnatural as the mirror must be rotated to meet the eyes of the subject, creating a visual situation in which the real arm is above the chest and the mirrored arm over the thigh. Apart from feeling unusual, this positioning can even be uncomfortable for the participant, and might reduce the embodiment of the mirrored limb. The problems of the CMB led to the invention of virtual reality (VR) and augmented reality (AR) mirror boxes (for a review see Cole, 2008). In a first approach, a 3-dimensional computer-generated version of the perceived phantom arm was presented on a screen and controlled via a wireless data glove on the intact arm (Desmond et al., 2006). A different approach used VR to transpose the movements made by an amputee's remaining limb into movements of a virtual limb (Murray et al., 2006a). These authors found a reduction of phantom pain intensity in 2 of 3 described cases (Murray et al., 2006b, 2007). The advantage of this system is that the entire body is implemented in the VR and thus complex hand–eye coordination is possible. However, none of these approaches has so far been used in a magnetic resonance imaging (MRI) scanner.

We developed a VR application for use inside a magnetic resonance scanner, with a variety of possibilities for controlling visual feedback. In order to be able to relate these data to previous findings obtained with the CMB setup, we performed a study in which we compared these two implementations in the same sample of subjects. We hypothesized that both approaches should lead to similar results for both subjective ratings and brain activation patterns.

2. Results

We found no significant differences in the reported intensity, vividness or perceived authenticity of the illusion between the VRMB and the CMB conditions (see Table 1), with ratings in both conditions ranging between 4.75 and 5.90.

Imaging data revealed three main foci of activation in the CMB condition (see Table 2 and Fig. 1a). We found significant task-related activation in the left primary motor (MI) and somatosensory cortex (SI), contralateral to the executed movement. Additional activation clusters were found bilaterally in the superior temporal gyrus and the medial temporal gyrus.

For the VRMB, we found task-related activation in the left MI extending into the left SI (see Table 2 and Fig. 1b). Additional activation was observed in the SMA, bilateral Rolandic operculum (secondary somatosensory cortex, SII), the right cerebellum, right supramarginal gyrus, left thalamus, right inferior and superior temporal gyrus as well as the left medial temporal gyrus. Activation of right MI (the side opposite to the mirrored movement) was present in both conditions (CMB and VRMB) after lowering the *p*-level to a less conservative value ($p < 0.0001$ uncorrected).

The contrast between conditions revealed significantly more task-related activation in the left SI extending into MI for the VRMB condition (see Table 2 and Fig. 1c).

The conjunction analysis showed a large cluster of task-related activation in left SI and MI (see Fig. 2). We also observed activation of the right MI (contralateral to the mirrored movement), right SII and the supplementary motor area. Additionally,

Table 1 – Rating results for the classical mirror box and the virtual reality mirror box conditions.

	CMB	VRMB	
Intensity of the illusion (m ± sd)	4.95 ± 2.1	4.90 ± 1.52	$t(20) = 0.14$, $p = 0.89$
Vividness of the illusion (m ± sd)	5.75 ± 1.68	5.90 ± 1.25	$t(20) = -0.51$, $p = 0.61$
Authenticity of the illusion (m ± sd)	5.20 ± 1.80	4.75 ± 1.76	$t(20) = 1.22$, $p = 0.24$

CMB = classical mirror box, VRMB = virtual reality mirror box; mean (m) and standard deviation (sd).
Scale from 1 = "as clear and vivid as a real sensory experience"/"like a true image of my hand" to 7 = "not at all clear and vivid"/"passive, like a movie".

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