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Force related hemodynamic responses during execution and imagery of a hand grip task: A functional near infrared spectroscopy study

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ABSTRACT

We examined force related hemodynamic changes during the performance of a motor execution (ME) and motor imagery (MI) task by means of multichannel functional near infrared spectroscopy (fNIRS). The hemodynamic responses of fourteen healthy participants were measured while they performed a hand grip execution or imagery task with low and high grip forces. We found an overall higher increase of [oxy-Hb] concentration changes during ME for both grip forces but with a delayed peak maximum for the lower grip force. During the MI task with lower grip force, the [oxy-Hb] level increases are stronger compared to the MI with higher grip force. The facilitation in performing MI with higher grip strength might thus indicate less inhibition of the actual motor act which could also explain the later increase onset of [oxy-Hb] in the ME task with the lower grip force. Our results suggest that execution and imagery of a hand grip task with high and low grip forces, leads to different cortical activation patterns. Since impaired control of grip forces during object manipulation in particular is one aspect of fine motor control deficits after stroke, our study will contribute to future rehabilitation programs enhancing patient's grip force control.

1. Introduction

The main reason for the occurrence of a stroke is an oxygen deficiency of the brain caused by a disturbance of the blood supply. This oxygen deficiency results in necrosis of the brain cells. The results of the brain cell damage frequently include lasting disability. Such disabilities can be speech disorders (aphasia/dysphasia), swallowing problems (aphagia/dysphagia), vision loss perception problems, vascular cognitive impairments (Sun, Tan, & Yu, 2014) and mild to severe motor impairments. Impaired control of grip forces during object manipulation in particular is one aspect of fine motor control deficits following cerebral stroke (Hermsdörfer, Hagl, Nowak, & Marquardt, 2003). Whereas cortical strokes affecting the cerebral cortex classically present with deficits such as neglect, aphasia, and hemianopia, subcortical strokes affect the small vessels deep in the brain, and typically present with purely motor hemiparesis affecting the face, arm, and leg. According to Langhorne et al., 80% of the disabilities caused by stroke are motor impairments, which include hemiparesis, incoordination and spasticity (Langhorne, Bernhardt, & Kwakkel, 2011; Langhorne, Coupar, & Pollock, 2009; Schaechter, 2004). In the first months after a stroke incident, the recovery of motor function due to rehabilitation care is most rapid. This recovery slows down and can reach a plateau by 6 months post-stroke (Hendricks, van Limbeek, Geurts, & Zwarts, 2002). The standard motor rehabilitation therapy typically involves a mix of physical and occupational training exercises (Schaechter, 2004) although current evidence suggests that motor imagery provides additional benefits to these conventional therapies. In the past years many studies reported on the beneficial role of motor imagery (MI) for motor rehabilitation, especially for stroke rehabilitation (Mihara et al., 2012; Pichiorri, Cincotti, et al., 2011; Pichiorri, Fallani, et al., 2011; Zimmermann-Schlatter, Schuster, Puhan, Siekierka, & Steurer, 2008). Several studies provided evidence that MI has an effect on the neural activation of motor areas, similar to real execution and affecting motor learning (Munzert et al., 2009; Ruffino, Papaxanthis, & Lebon, 2017; Schuster et al., 2011). In addition, MI training has similar effects like motor training, which both result in a more specific activation of the motor cortical areas and an increase in motor performance after training (Gentili, Han, Schweighofer, & Papaxanthis, 2010; Kaiser et al., 2014; Nyberg, Eriksson, Larsson, & Marklund, 2006; Zhang et al., 2011). This is in line with one core assumption of the "simulation hypothesis" (Jeannerod, 1994), where the mental rehearsal of a movement activates the same cortical areas like an actual motor preparation

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and execution. Furthermore, MI can be performed in two different ways, either visual (here we further subdivide into 1st person and 3rd person view) or kinaesthetic, leading to different cortical activation patterns. During a kinaesthetic MI, the focus is on the kinaesthetic experience of a movement while avoiding muscle tension. Visual imagery on the other hand is the mental visualization of a scene, in which the specific movement is executed. For example, Neuper, Scherer, Reiner, and Pfurtscheller (2005) compared these two different types of MI and observed stronger activation in motor-related areas during kinaesthetic MI. Moreover kinaesthetic MI has already been used for investigating the cortical reorganization processes after a stroke which are induced by the damaged brain in order to compensate for the motor deficits by extending the functional scope of the intact areas of the brain (Calautti & Baron, 2003). Furthermore the ongoing reorganization has been proven to be in relation to the recovery of motor functions (Schaechter, 2004; Ward, Brown, Thompson, & Frackowiak, 2003). Ward et al. (2003) furthermore showed a clear relationship between task-related activation of the motor system and outcome after stroke. Moreover, they showed in a later study (2006) that premotor regions play a functionally relevant role in optimizing motor output and that neural reorganization after stroke is a dynamic process depending on anatomy of damage and the demands of a task.

Although in the past years new knowledge about the recovery and reorganization of neural networks after stroke was achieved, its translation in clinical settings is still problematic. Many stroke patients still have some degree of motor impairment after completing a standard rehabilitation program. Currently some rehabilitation centres already use computer-aided therapy which offers patients with neurological disorders a new and promising path to recovery. For example, a special sensor handle enables the measurement of the power grip in the human hand. This system, integrated in interactive therapy games, supports patients in recovering their lost hand functions at different levels (Wiederhold & Riva, 2013). One possible rehabilitation training exercise is the performance of a hand grip task. This exercise can be used to objectively assess the training progress, because of the possibility to measure the used force of the hand grip. Another advantage of a hand grip exercise is the fact that the ability to perform a hand grip after a stroke returns earlier than single finger movements, and therefore can be used for training earlier after stroke (Ward et al., 2003).

Based on this knowledge we used a hand grip exercise, the strength of which was additionally measured by a commercially available sensor handle. The hemodynamic responses (reflecting activity) during the specific hand grip exercises were simultaneously measured by means of functional near infrared spectroscopy (fNIRS). fNIRS is an emerging non-invasive optical technique for the in vivo assessment of cerebral oxygenation. In the following, the concentration of oxygenated haemoglobin (oxy-Hb) and deoxygenated haemoglobin (deoxy-Hb) is denoted as [oxy-Hb] and [deoxy-Hb]). In recent years multichannel fNIRS has been used to study functional activity of the human cerebral cortex (for a review see e.g. Cutini, Moro, & Bisconti, 2012; Dieler, Tupak, & Fallgatter, 2012; Leff et al., 2011;) and is becoming an established research tool in neuro-rehabilitation (for an overview see e.g. Arenth, Ricker, & Schultheis, 2007; Scholkmann et al., 2014). Furthermore there are also a few studies utilizing fNIRS to investigate neurocognitive processes associated with neurological and psychiatric disorders (Ehlis, Bähne, Jacob, Herrmann, & Fallgatter, 2008; Hock et al., 1997; Irani, Platek, Bunce, Ruocco, & Chute, 2007). We have chosen this method since it is currently a well-established and promising neuroimaging tool for scientifically motivated studies of healthy volunteers but could also be easily integrated in the diagnostic and monitoring of stroke patients. (Aries et al., 2012; Budohoski et al., 2012; Obrig, 2014; Obrig & Steinbrink, 2011).

In the present study the neural correlates of ME and MI of a hand grip task with two different grip forces were investigated by fNIRS. We hypothesize that the hemodynamic response during MI and ME of the hand grip exercise is correlated with the grip force used. Based on the literature we further assume that the cortical activity during the performance of ME will be higher for both grip strength compared to MI.

2. Methods

2.1. Participants

Thirteen right-handed healthy participants took part in this study, five females and nine males. The mean age of the participants was 25 ± 3 years (mean ± SD). All participants had normal or corrected to-normal vision, and no experience with motor imagery prior to this study. The study was approved by the local ethics committee (Medical University of Graz) and is in accordance with the ethical standards of the Declaration of Helsinki. After a detailed written and oral instruction they gave informed written consent to participate in the study.

2.2. Experimental procedure

The participants were seated in a comfortable armchair in a dimmed cabin about 1.4 m in front of a monitor. After the montage and calibration of the fNIRS system the sensor handle was fixed on the right hand and the participants had to grip (palmar grasp) it as forceful as possible five times. The maximum grip strength (MGS) of each participant was calculated by averaging the performed five trials. A test run was presented on the monitor allowing the participants to become familiar with the tasks and the sensor handle device. The measurement consisted of an alternation of runs with MI and ME. Every participant underwent six runs, three runs with ME, and three runs with MI, in randomized order. Irrespective of whether the condition was MI or ME, the experimental design of a run was the same. Every run consisted of 20 trials (10 trials with 20% of the MGS, 10 trials with 40% of the MGS), with a random alternation of the trials. The two grip strength, 20% and 40% were chosen based on the results of a prior fNIRS pilot study where we compared 20%, 40% (Ward et al., 2003) and 60% of the MGS. In this pilot study participants performed 40 trials (1 trial lasted 10 s) of a hand grip task with each force. We found that the hand grip task with 60% of the MGS was too exhausting and participants were not able to produce the required force during the whole trial. Furthermore we found more artefacts in the fNIRS data. The grip forces of 20% and 40% of the MGS showed distinct brain activity and could be executed easily. To ensure a consistent kinematic performance we have chosen these grip forces of 20% and 40% of the MGS (Ward et al., 2003) for the main experiment. The timeline of a trial can be seen in Fig. 1. The start was indicated by the appearance of three white lines, encouraging the participants to concentrate on the screen. After one second, one of the lines disappeared and the remaining red line represents the requested hand grip strength during this trial. To control the grip strength, the instantaneous gripping force measured by the sensor handle was provided in form of a white feedback bar. This feedback bar appeared at the start of the task performance, indicating the current grip strength. The stronger a subject gripped the sensor handle, the longer the feedback bar was. As the correct grip strength was indicated by a green line, the participants were able to adjust their current grip strength according to the feedback bar. After 10 s hand grip performance, the screen turned black and the inter-trial interval, with a duration randomly varying between 10 and 14 s, started.

For the ME condition, the participants were instructed to continuously perform a hand grip whereas the target strength was indicated by the red line on the screen. Participants had no problems to press the sensor handle with both forces for several times in 10 s. The MI condition followed the same procedure, but instead of the execution of a hand grip, the imagination of a kinaesthetic experience of such a hand grip had to be performed. Before the start of the experiment, participants performed several imagery trials to get familiar with the task. Since Holper and Wolf found higher activation during MI tasks with feedback than without feedback (Holper & Wolf, 2010), sham