Neuroscience 343 (2017) 85–93

FUNCTIONAL BRAIN IMAGING OF WALKING WHILE TALKING – AN FNIRS STUDY

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Abstract—Since functional imaging of whole body movements is not feasible with functional magnetic resonance imaging (fMRI), the present study presents *in vivo* functional near-infrared spectroscopy (fNIRS) as a suitable technique to measure body movement effects on fronto-temporo-parietal cortical activation in single- and dual-task paradigms. Previous fNIRS applications in studies addressing whole body movements were typically limited to the assessment of prefrontal brain areas. The current study investigated brain activation in the frontal, temporal and parietal cortex of both hemispheres using functional near-infrared spectroscopy (fNIRS) with two large 4 × 4 probe-sets with 24 channels each during single and dual gait tasks. 12 young healthy adults were measured using fNIRS walking on a treadmill: the participants performed two single-task (ST) paradigms (walking at different speeds, i.e. 3 and 5 km/h) and a dual task (DT) paradigm where a verbal fluency task (VFT) had to be executed while walking at 3 km/h. The results show an increase of activation in Broca's area during the more advanced conditions (ST 5 km/h vs. ST 3 km/h, DT vs. ST 3 km/h, DT vs. 5 km/h), while the corresponding area on the right hemisphere was also activated. DT paradigms including a cognitive task in conjunction with whole body movements elicit wide-spread cortical activation patterns across fronto-temporo-parietal areas. An elaborate assessment of these activation patterns requires more extensive fNIRS assessments than the traditional prefrontal investigations, e.g. as performed with portable fNIRS devices.

Key words: functional near-infrared spectroscopy, dual task, gait, verbal fluency task, gait imaging.

INTRODUCTION

'Walking while talking' is a common action which we perform seemingly without effort on a day-to-day basis. In addition, it comprises an interesting combination of two individual activities which are – from a neurophysiological perspective – complex in and of themselves. Walking while talking can be understood as an example of the classical dual task (DT) combination in which walking is combined with a cognitive task. Such paradigms involve executive functioning (Ble et al., 2005; Verghese et al., 2007; Al-Yahya et al., 2011). Both executive function and gait performance have been shown to be closely associated with frontal lobe function, whereas walking/gait is specifically related with activity in the primary motor cortex, the supplementary motor area, and the premotor cortex (Miyai et al., 2001; Suzuki et al., 2004). In elderly individuals particularly, gait parameters such as gait speed and stride-time variability are diminished, especially under dual task conditions, i.e. in combination with a cognitive task (Lindenberger et al., 2000; Verhaeghen et al., 2003; Hausdorff et al., 2008). These effects correlate with prefrontal volumes measured with structural brain imaging (Rosano et al., 2012). Even in younger adults task performance speed seems to be reduced when two or more tasks are combined in a DT paradigm (Yogev-Seligmann et al., 2010). In the elderly, the performance in DT is considered as a marker for the cognitive state. Hence, patients with Alzheimer's Disease walk more slowly and with decreased gait parameters in addition to having more constraints in DT parameters. Corresponding findings have been observed in elderly with mild cognitive impairment, a possible prodromal phase of Alzheimer's Disease (Sheridan et al., 2003; Pettersson et al., 2005; Gillain et al., 2009; Muir et al., 2012).

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Abbreviations: ANOVA, analysis of variance; DT, dual task; CBSI, Correlation Based Signal Improvement; fMRI, functional magnetic resonance imaging; fNIRS, functional near-infrared spectroscopy; HHb, deoxygenated hemoglobin; O_2Hb, oxygenated hemoglobin; ROI, region of interest; ST, single task; VFT, verbal fluency test.

http://dx.doi.org/10.1016/j.neuroscience.2016.11.032
0306-4522/

These results emphasize the implementation and impact of DT actions on daily life, especially for individuals at risk or in early stages of neurodegenerative diseases. A better understanding of the neurobiological nature of these mechanisms requires the assessment of brain activation while patients perform DT paradigms. While walking in combination with a cognitive task might have the strongest relevance for everyday life in the elderly (see above), DTs that involve whole body movements such as walking represent the biggest challenge to functional brain imaging due to the massive motion artifacts they produce. In fact, functional magnetic resonance imaging (fMRI), one of the most frequently used functional imaging methods in brain research, cannot be combined with real-time walking DT paradigms since locomotion is not possible in an fMRI scanner. Instead of real walking, the subject imagines walking as a typical surrogate in fMRI studies on cortical motor activation (la Fougere et al., 2010; Personnier et al., 2010; Zwergal et al., 2012). Recently, brain activation in elderly individuals with gait problems has been studied using this so called ''imagery'' techniques (Gillain and Petermans, 2013; Peterson et al., 2014a,b). Imagining gait seems to be an elegant approach for assessing movement-related cortical activation patterns without having locomotion executed in a scanner (Blumen et al., 2014; van der Meulen et al., 2014) but also without sensory afferents. However, the ecological validity of these studies is very limited as the results can hardly be generalized to situations that involve actual real-time locomotion. Recently, first studies using EEG imaging techniques showed first results in mapping of brain activation under walking conditions in pilot studies (Gwin et al., 2010; Petersen et al., 2012; Ehinger et al., 2014; Seeber et al., 2015).

The technique of functional near-infrared spectroscopy (fNIRS), in contrast to fMRI, tolerates moderate locomotion and therefore allows us to investigate real-time individual abilities instead of just imagery of actions. Therefore, fNIRS can be used for studying brain activation while walking or while performing different tasks that may contain gait. The direct functional measurement of gait maps on prefrontal and premotor cortical activation, depending on the walking speed, as well as sensorimotor regions independent of gait speed (Miyai et al., 2001; Suzuki et al., 2004). Comparisons of gait cortical activation and related tasks, such as preparation of gait, are also feasible with the fNIRS technique (Suzuki et al., 2008). Due to the comparably uncomplicated and comfortable handling of the method, elderly and also impaired individuals can be measured with fNIRS particularly well while performing motor (e.g. gait) tasks (Harada et al., 2009; Rea et al., 2014).

In combination with cognitive tasks, which are much more frequently used in fNIRS studies, the method is also well suited for investigating dual task conditions such as walking while counting (Mirelman et al., 2014), while conducting tasks that require executive function (Doi et al., 2013), or while talking or checking boxes (Beurskens et al., 2014). A very common cognitive task particularly applied in fNIRS-studies is the verbal fluency task (VFT) which has been shown to reliably produce activation of prefrontal areas (Herrmann et al., 2003, 2006). Psychiatric illnesses such as schizophrenia and depression show decreased cerebral activation during the VFT (Ehlis et al., 2007; Pu et al., 2008; Marumo et al., 2014). Healthy elderly display less focused prefrontal activation (Heinzel et al., 2013; Pu et al., 2014), and the VFT has been used in combination with fNIRS to detect abnormalities in demented elderly and the effects of anti-dementia drugs (Richter et al., 2007; Herrmann et al., 2008; Metzger et al., 2015).

Existing DT studies using fNIRS concentrated on the prefrontal cortex which seems to have a crucial role in DT versus ST. Unfortunately, these previous dual-task studies generally used only a very small number of NIRS channels, sometimes only two, located exclusively in the frontal area (Holtzer et al., 2011; Doi et al., 2013; Beurskens et al., 2014; Mirelman et al., 2014).

In contrast to this approach, fMRI studies suggest a network of activated (e.g. supplementary motor or visual cortex) and deactivated (e.g. posterior insula, parietoinsular vestibular gyrus, superior temporal gyrus) brain areas (la Fougere et al., 2010; Zwergal et al., 2012) during walking imagery. Considering this evidence, we hypothesize that – besides prefrontal areas – additional brain regions, such as premotor, temporal, or parietal areas show activation changes during a DT paradigm involving walking. To test this hypothesis, a multichannel fNIRS measurement focusing on broader areas that are not limited to the prefrontal cortex is needed.

EXPERIMENTAL PROCEDURES

Subjects

The study was reviewed and approved by the ethics Committee of the University of Tuebingen (90/2009BO2, 4th. amendment) and all procedures involved were in accordance with the latest version of the Declaration of Helsinki. Prior to inclusion, written informed consent was obtained from the participants after detailed information about the study procedure had been provided. 12 subjects (eight female) were recruited out of the staff of the Department of Psychiatry and Psychotherapy at the University of Tuebingen. Mean age was 27.6 (range: 19–39) years. All participants were right handed, as assessed by means of the Edinburgh Handedness Inventory (Oldfield, 1971) and did not have any psychiatric or severe neurological (e.g., epilepsy, encephalitis) diseases, neither current nor in the past, as examined by a psychiatrist.

Dual task paradigm

The measurement consisted of three conditions: Walking as a ST paradigm at a velocity of 3 km/h (slow walk condition) and 5 km/h (fast walk condition), respectively, as well as the dual task (DT) paradigm which combined walking at a velocity of 3 km/h with the VFT. Walking was performed on a treadmill (saturn 2.0, h/p/cosmos, Nussdorf-Traunstein, Germany) with preset walking speed. The participants were instructed to keep their step