International Journal of Psychophysiology 92 (2014) 122–128

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Age-related changes in prefrontal activity during walking in dual-task situations: A fNIRS study☆,☆☆

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ARTICLE INFO

Article history:
Received 22 November 2013
Received in revised form 10 March 2014
Accepted 17 March 2014
Available online 25 March 2014

Keywords:
fNIRS
Aging
Locomotion
Neural activation
Executive function
Dual-task walking

ABSTRACT

Background: Previous studies suggest that the human gait is under control of higher-order cognitive processes, located in the frontal lobes, such that an age-related degradation of cognitive capabilities has a negative impact on gait.
Methods: Using functional Near-Infrared-Spectroscopy (fNIRS) we investigate the frontocortical hemodynamic correlates of dual-task walking in two conditions. 15 young and 10 older individuals walked on a treadmill while completing concurrent tasks that had either visual (checking) or verbal-memory (alphabet recall) demands. We compared subjects' motor performance, as well as their prefrontal activity in single- and dual-task walking.
Results: Our behavioral data partly confirm previous accounts on higher dual-task costs in stepping parameters (i.e., decreased step duration) in old age, particularly with a visual task and negative dual-task cost (i.e., improved performance) during the verbal task in young adults. Functional imaging data revealed little change of prefrontal activation from single- to dual-task walking in young individuals. In the elderly, however, prefrontal activation substantially decreased during dual-task walking with a complex visual task.
Conclusion: We interpret these findings as evidence for a shift of processing resources from the prefrontal cortex to other brain regions when seniors face the challenge of walking and concurrently executing a visually demanding task.

1. Introduction

The gait pattern changes in old age. For instance swing time, swing time variability, stride-time variability and walking speed decrease, while cadence, step length and stride time increase (Mills and Barrett, 2001; Schrager et al., 2008). These changes are associated with an increased risk of falling and a decreased quality of life (Newman et al., 2006). Age-related gait changes are more pronounced when walking is combined with another, concurrent task, which suggests that cognition plays a role as a mediating factor (Li et al., 2001; Lindenberger et al., 2000; Al-Yahya et al., 2011; Beurskens and Bock, 2011; Verhaeghen et al., 2003). Specifically, age-related decrements of dual-task walking depend on the visually specified constraints on walking (Beurskens and Bock, 2012) and are particularly pronounced when the non-walking task is visually demanding (Beurskens and Bock, 2011, 2012, 2013; Bock, 2008), possibly because it is difficult for the brain's executive system to coordinate navigation through visually defined space with another visual task.

The above interpretation calls for an experimental verification by studies that relate deficits of dual-task walking to measures of brain activation. However, it is difficult to use technologies such as functional magnetic resonance imaging (fMRI) or electroencephalography (EEG) during locomotion, since especially fMRI requires still and stabilized subjects and is not applicable during locomotion. To overcome this problem, some researchers substituted actual movements by motor imagery (la Fougere et al., 2010; Zwergal et al., 2012; Personnier et al., 2010). Brain activation is similar during real and imagined locomotion in young (la Fougere et al., 2010) and older adults (Zwergal et al., 2012), but motor imagery performance was not (Personnier et al., 2010), such that substitution of gait by imagery may confound deficits of locomotion with those of imagery. The present study therefore uses an alternative approach for measuring brain activation. We utilize functional near-infrared spectroscopy (fNIRS), which has already been applied with success during active movements (Leff et al., 2011; Miyai

☆ Authors' contributions: All authors have read and concur with the content in the final manuscript. The material within has not been and will not be submitted for publication elsewhere except as an abstract. All authors have made substantial contributions to all of the following:(1) Conception and design of the study (RB and OB),(2) Acquisition of data, or analysis and interpretation of data (RB, IH, RR, OB),(3) Drafting the article or revising it critically for important intellectual content (RB, IH, OB),(4) Final approval of the version to be submitted (RB, IH, RR, OB).

☆☆ Conflict of interest: The authors are not aware of any conflict of interest.

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http://dx.doi.org/10.1016/j.ijpsycho.2014.03.005
0167-8760/

et al., 2001). Converging evidence with this technique suggests that single-task walking draws on higher-order cognitive resources (Verghese et al., 2007) and engages the prefrontal, premotor, and primary sensorimotor cortex differently in healthy young (Miyai et al., 2001; Suzuki et al., 2008) and older adults (Harada et al., 2009). Further work has shown that prefrontal activation increases during mental preparation for a subsequent walking task (Suzuki et al., 2008) and that in elderly subjects, prefrontal activation increases substantially when walking at 70% rather than 30% or 50% of the individuals' maximum walking speed (Harada et al., 2009).

To our knowledge, only one study used fNIRS to compare prefrontal activation during single- and dual-task walking (Holtzer et al., 2011). The dual-task condition was "walking while talking" (WWT) where locomotion was combined with verbal alphabet recall. The study found a higher prefrontal activation in dual- compared to single-task walking, and this increase was slightly more pronounced in young than in older subjects. This outcome stands in contrast to cognitive resource theories of aging which posit that the increase of brain activity with increasing task demands is more rather than less pronounced in old age (Steffener and Stern, 2012) or that with advancing age and task demand older adults utilize additional contralateral brain areas. For example, the HAROLD model (Cabeza, 2002) posits that elderly recruit additional brain areas, not used by young subjects, to maintain performance at an acceptable, albeit reduced level (Reuter-Lorenz, 2002). This model primarily affects the lateralization of prefrontal activity during cognitive performances, i.e. an activation shift from one hemisphere to another. Neural activity tends to be less lateralized in older adults compared to young adults. However, other recent theories agree with the findings of Holtzer et al. (2011). In cognitive reserve theory, Stern (2009) introduced the mechanism of neural compensation. The primarily used network can no longer support the performance needed to accomplish the task and an alternative network, which is normally not used, is recruited. This secondary network is not as optimal as the primary one to sustain performance and a performance decrease emerges. The CRUNCH model (Reuter-Lorenz and Cappell, 2008) agrees with this view, and additionally states that older adults reach a resource ceiling as task demand increases, which results in under-activation relative to young adults (Reuter-Lorenz and Lustig, 2005).

The present study was designed to replicate and validate the available fNIRS study (Holtzer et al., 2011) and compare the previously used WWT with a visual checking task that has been shown to be even more effective to increase dual-task decrements in older adults. We have shown before that tasks with visual requirements produce larger deficits of dual-task walking in old age than tasks without such requirements (Beurskens and Bock, 2011, 2012, 2013; Bock and Beurskens, 2010), and therefore expected that age differences in prefrontal activation will be even more pronounced with the checking task than with the WWT task. Specifically, we expected according to the above experimental and theoretical findings that (a) young participants will show increased prefrontal lobe activation during dual-task walking with WWT as well as with checking, (b) older participants will show a slightly less increase with WWT (based on the aforementioned study by Holtzer et al. (2011)), but a distinctly less increase with checking (based on neural compensation processes, i.e. cognitive reserve and CRUNCH theories), and c) there will be a substantial relationship between neural activation pattern and behavioral outcome.

2. Methods

2.1. Subjects

Fifteen young (age: 24.5 ± 3.3 years, height: 173.3 ± 5.9 cm, mass: 68.6 ± 11.8 kg) and ten older subjects (age: 71.0 ± 3.8 years, height: 175.9 ± 9.8 cm, mass: 84.3 ± 11.1 kg) participated in this study. All subjects were independently community-dwelling and had not participated in research on dual-task locomotion, neural activity or cognition within the preceding 12 months. All reported to be free of muscular or orthopedic impairment and had normal or corrected-to-normal eyesight. All arrived without help at the agreed-upon time in the agreed-upon place, properly followed our instructions and adequately completed a questionnaire regarding their personal circumstances (e.g., address, date of birth, medication). Thus, we deemed them to be free of gross cognitive impairment because the cognitive demands of these questionnaires are similar to the mini mental state examination that is widely used in literature (U'Ren et al., 1990). Before participating, all subjects signed an informed consent statement preapproved by the authors' institutional Ethics Committee.

2.2. Behavioral tasks

Participants were asked to walk on a motor-driven treadmill (Zebris FDM-T treadmill system, Isny, Germany). Prior to the actual data collection, they walked on the treadmill for approximately 5–10 min to familiarize with the instrument and to select the preferred individual walking speeds in each walking condition. These speeds were maintained throughout the subsequent experiment. The following tasks were administered twice to each subject for 30 s, in a counterbalanced order:

- *walk*: subjects walked on the treadmill
- *check*: seated subjects held with their non-dominant hand a sheet of paper (21.0 × 29.5 cm), on which 65 squares (1.0 × 0.8 cm) were drawn in 5 columns of 13 rows. They were instructed to check each box as quickly as possible by an "X", using a pen in their dominant hand; they were to start with the top left box, and proceed from top to bottom, column by column, until 30 s expired (Bock and Beurskens, 2011),
- *talk*: seated subjects were asked to call out loud every second letter of the alphabet as fast as possible, starting from "A" in the first round and from "B" in the second (Holtzer et al., 2011), until 30 s expired,
- *walk & check*: concurrent walk and check,
- *walk & talk*: concurrent walk and talk, and
- *rest*: subjects were sitting on a chair.

Participants' walking performance was measured by a capacitive pressure sensor matrix (94.6 × 40.6 cm) underneath the treadmill's walking surface (150 x 50 cm). The measuring range was 1–120 N/cm^2 with an accuracy of ± 5% and a threshold of 1 N/cm^2; the sampling frequency was set to 100 Hz. The pressure data was used to determine the following gait measures:

- *step duration*: time between two consecutive heel strikes of the right foot,
- *step length*: distance between heel strike of one side and heel strike of the contra-lateral side in the same step cycle, and
- *number of steps*: step cycles within 30 s.

We then calculated the mean of each gait measure for each subject and task, discarding the first and last cycles to exclude transients. For each subject and task, we also determined:

- *checking-speed*: number of checked boxes per second and
- *talking-speed*: number of correctly recited letters per second

To quantify subjects' ability to execute both, the walking and the additional cognitive task concurrently, we calculated the difference between single- and dual-task performances (DTC) for each parameter, subject and task separately, and normalized the outcome by dividing it by the mean standard deviation of the pertinent single task and age group. We thus yielded dimensionless scores which can be averaged across walking and non-walking measures to yield the mean dual-task costs (mDTC) across both concurrent task (Beurskens and Bock, 2013); this composite value deconfounds dual-task costs from task priority assignments (Bock, 2008; McDowd, 1986).

2.3. fNIRS measurement

Changes of cerebral oxygenation levels were recorded by a near-infrared optical tomographic imaging device (DYNOT Imaging System, NIRx MEDICAL TECHNOLOGIES, LLC. Wavelengths 760 nm, 830 nm, Samplingrate 1.81 Hz). NIRS is a technique to detect changes in cerebral oxygenation in response to functional stimulation (Obrig and Villringer, 2003). Sixteen optodes, stabilized by a custom-made plastic hard shell, were placed between 2.2 cm (optodes 1–6) and 2.5 cm (optodes 7–16) apart above the subjects' frontal lobes (Fig. 1).

Optode position was set according to the international 10–20-system (Klem et al., 1999) with FPz located between optodes 8 and 9 (cf. Fig. 1). Channels were calculated as midpoints between each emitter-detector combination. We thus yielded 14 channels of measurement. The channel positions of each participant were transformed into the standard brain from the Montreal Neurological Institute (MNI space) according to Singh et al. (2005), using a 3D digitizing system (Zebris 3D Measuring Systems, Zebris Medical GmbH). Talairach coordinates (Talairach and Tournoux, 1988), brain sub-regions and according Brodmann areas are displayed in Table 1. Channels covered corresponding brain regions above both hemispheres, covering the middle and superior frontal gyrus. All tasks were conducted in a quiet, dimly illuminated room.

Oxygenated (HbO_2) and de-oxygenated (HbR) blood levels (cf. Cope et al., 1988) were determined using NIRS-SPM (Jang et al., 2009; Tak et al., 2010; Ye et al., 2009), a software based on Statistical Parametric Mapping (Ye et al., 2009) and Matlab (Matlab 7.10 (R2010a), The Mathworks, Inc. Natick, MA, USA). Calculations followed established procedures (Cope et al., 1988). Each channel of individual participants was visually inspected and movement artifacts were corrected using a technique developed by Scholkmann et al. (2010), which is based on moving standard deviation and spline interpolation. In a first step, the moving standard deviation of the data series was calculated and secondly, individual thresholds were specified to allow artifact detection. In a last step, sections containing movement artifacts were spline interpolated and the data series was reconstructed (Scholkmann et al., 2010). Each fNIRS data set for walking conditions (*walk*, *walk & check* and *walk & talk)* was baseline-corrected by subtracting each walking condition individually from our rest condition. Hence, the changes in HbO_2 and HbR for *walk*, *walk & check* and *walk & talk* were normalized to the same level of the baseline condition. The data were subsequently filtered using the pre-coloring method (Worsley and Friston, 1995), which corrects for temporal correlations that might otherwise inflate the calculated significance levels. This method essentially represents a Gaussian or a HRF (hemodynamic response function) lowpass filter (Jang et al., 2009; Ye et al., 2009); the present work uses the HRF filter, which is the preferred choice for NIRS data since it is based on frequencies of modeled neuronal signals, which represent the best fit for hemodynamic NIRS data (Jang et al., 2009; Ye et al., 2009). Possible global trends due to breathing, heartbeat, vasoconstriction or other experimental influences were removed by the wavelet-minimum description length (MDL) de-trending algorithm (Jang et al., 2009). To decompose the NIRS data series into bias, hemodynamic signal, and noise components in distinct scales, a wavelet transform is applied to the time series. The hemodynamic response was modeled using a boxcar function convolved with a canonical hemodynamic response function (Ye et al., 2009). Data were then analyzed using a general linear model estimation to obtain concentration changes of HbO_2 and HbR for each of the walking conditions (*walk*, *walk & check*, *walk & talk*). To rule out that effects found in our fNIRS measurements are attributed to walking demands only, we contrasted dual-task walking to single-task walking. Comparable to the fMRI BOLD signal, high synaptic activity leads to an increase in blood flow, which is indicated by a higher level of oxygenated blood in fNIRS. The highest relationship has indeed been found in correlation analyses between BOLD signals and cerebral blood flow measured by fNIRS (Strangman et al., 2002). According to this, an increase of oxygenated blood flow and a reduced deoxygenated blood flow are both seen as signs of increased cerebral activity (Villringer et al., 1993).

Table 1
Talairach coordinates (x,y,z) of fNIRS channels, according brain regions and Brodmann areas (BA).

ch. #	Hemisphere	Brain region	BA	x	y	z
1	Left	Middle frontal gyrus	10	−28	67	10
2		Middle frontal gyrus	10	−34	65	1
3		Superior frontal gyrus	10	−31	65	−10
4		Superior frontal gyrus	11	−14	70	−11
5		Superior frontal gyrus	10	−16	72	13
6		Superior frontal gyrus	10	−8	72	12
7		Superior frontal gyrus	11	−7	71	11
8	Right	Superior frontal gyrus	11	10	70	−16
9		Superior frontal gyrus	10	12	73	12
10		Superior frontal gyrus	10	22	72	11
11		Superior frontal gyrus	10	21	69	−14
12		Superior frontal gyrus	10	32	65	−15
13		Middle frontal gyrus	10	38	65	1
14		Middle frontal gyrus	10	32	67	9

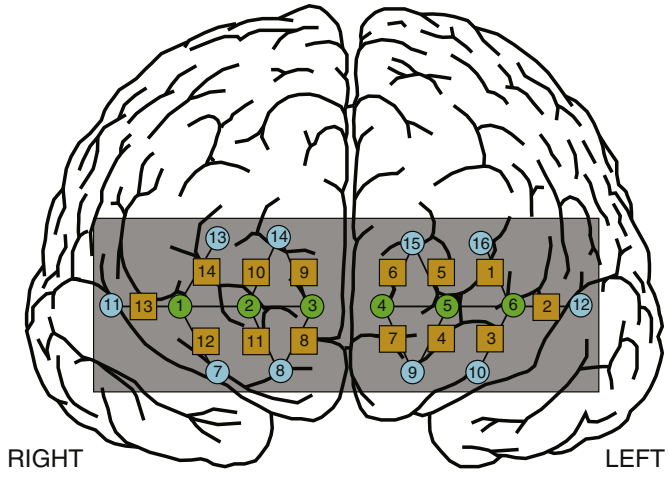

Fig. 1. Simplified schematic drawing of optode positions and the appropriate channel positions on subjects' prefrontal cortex. Light green optodes represent light-emitting sources and light blue optodes represent light-absorbing detectors. Channels and their numbers are presented as yellow boxes between the optodes.

2.4. Data analyses

The mDTC of each walking measure were submitted to analyses of variance (ANOVAs) with the between-factor Age (*old*, *young*) and the within-factor Condition (*walk & check*, *walk & talk*). Statistical significance of the intra-condition differences of HbO_2 and HbR was analyzed using two- sided, one-sample t-tests. To restrict alpha inflation due to multiple statistical comparisons, only significant results that exceed a threshold of $p < 0.05$ are reported and Sun's tube formula, implemented in NIRS-SPM (Ye et al., 2009), was used for p-value correction (Loader and Sun, 1997). NIRS measures of HbO_2 and HbR were then submitted to separate ANOVAs with the between-factor Age (*old*, *young*) and the within-factors Condition (*walk & check*, *walk & talk*), Lateralization (*left*, *right*) and Channel (*1–14*). To analyze the associations between brain activation levels (HbO_2/HbR) and locomotion (step duration, step length and number of steps), we conducted regression analyses. Multiple correlations were corrected using Bonferroni corrections. All statistical analyses were done using STATISTICA 10 (StatSoft, Inc., Tulsa, OK, USA).

3. Results

Fig. 2 displays our three measures of dual-task walking separately for each age group and task combination (unprocessed walking data from conditions *walk*, *walk & check* and *walk & talk* and secondary task data for *talking* and *checking* can be obtained from Suppl. #01 A–E, online). Table 2 summarizes the pertinent ANOVA results. Both presentations show that mDTC were larger in old age and that they were larger in *walk & check* compared to *walk & talk*. Post-hoc comparisons indicated significantly lower mDTC during *walk & talk* in young compared to older adults ($p < 0.05$, $p < 0.05$ and $p < 0.01$ for step duration, step length and number of steps respectively), significantly lower mDTC during walk & talk compared to walk & check in young adults (all $p < 0.001$), significantly higher mDTC in walk & check compared to walk & talk in older adults' step duration ($p < 0.05$), and no group difference for walk & check ($p = 0.11$, $p = 0.20$ and $p = 0.16$ for step duration, step length and number of steps respectively). Thus, the significant age × condition effect is mainly based on increasing mDTC from *walk & talk* to *walk & check* in young adults (i.e., performance improvement in *walk & talk and* slight performance deterioration in *walk & check*), while older adults have generally higher mDTC than young adults but statistically similar mDTC in both conditions, although there is a tendency towards an increase during *walk & check*.

Fig. 3 shows individual raw data from one older and one young participant and for one exemplarily chosen channel of the fNIRS measurement, representative for each age-group. Data displayed is prior to any processing and de-trending. It can be seen that HbO_2 did not change with increasing task demands (i.e., *walk*, *walk & check*, *walk & talk*) in young subject, while older subjects' neural activation decreased in condition *walk & check* (Fig. 3, dashed line) but not in the other two conditions (Fig. 3, solid and dotted lines).

Fig. 4 displays the contrasts of cortical activation during *walk & check* or *walk & talk* on the one hand, and *walk* on the other hand for each age group and for each NIRS channel separately. The pertinent ANOVA outcomes are summarized in Table 3.

To rule out effects of different activation levels during single-task walking, we compared subjects' hemodynamic responses during condition *walk*. Mean neural activations across all channels did not differ between young and older adults for HbO_2 ($t(22) = -0{,}39$; $p = 0.71$) and for HbR ($t(22) = -0{,}98$; $p = 0.34$). According to the ANOVA outcomes, the hemodynamic response during dual-task walking differed little from that during single-task walking in young subjects under both dual-task conditions and in older subjects during condition *walk & talk*. However, a distinct difference emerged for older subjects in condition *walk & check* (i.e., significance of Age x Condition for both parameters, cf. Table 3). Specifically, older subjects showed lower levels of oxygenated and higher levels of de-oxygenated blood in *walk & check* than in *walk*. This was the case for 12 of the 14 registered channels, only channel 02 and channel 11 showed increased HbO_2 and decreased HbR (cf. Fig. 4). Since a decrease of HbO_2 and an increase of HbR are both taken as signs of reduced brain activity (Villringer et al., 1993), we thus found evidence that in condition *walk & check*, seniors' brain activity was reduced throughout a broad region in both prefrontal hemispheres. This finding is supported by the fact that we did not find significant effects of Lateralization in our ANOVAs ($F(1,22) = 0.39$; $p = 0.54$ for HbO_2 and $F(1,22) = 1.09$; $p = 0.31$ for HbR). Both hemispheres seem to be affected in a similar way during *walk & check*.

Table 2
ANOVA outcomes: walking measures.

	Age	Condition	Age × condition
Step duration	$F(1,22) = 7.95^{**}$	$F(1,22) = 23.63^{***}$	$F(1,22) = 1.09$ n.s.
Step length	$F(1,22) = 7.62^{*}$	$F(1,22) = 21.90^{***}$	$F(1,22) = 4.32^{*}$
Number of steps	$F(1,22) = 10.53^{**}$	$F(1,22) = 29.06^{***}$	$F(1,22) = 6.62^{*}$

n.s., *, ** and *** indicate $p > 0.05$, $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.

To determine whether our fNIRS data show valid associations between neural activation and dual-task walking, we correlated the decrease in HbO_2 that we found during *walk & check* in older subjects with their pertinent mDTC. The correlations ranged between $r = 0.08$ and $r = 0.85$, but only the decrease in HbO_2 for channel #06 was significantly correlated to mDTC for step duration and number of steps. However, after correcting for multiple comparisons, the only significant association remained between channel #06 and the number of steps ($r = -0.85$, $p = 0.04$). Lower neural activity is associated with increased dual-task costs during our complex task condition *walk & check*.

4. Discussion

The present study used fNIRS to investigate the hemodynamic correlates of dual-task walking in young and older individuals. We combined walking with a concurrent visual (checking) or verbal (alphabet recall) task, and compared subjects' motor performance as well as their prefrontal activity to those in single-task walking. According to established literature, we expected that motor performance will be poorer and prefrontal activity higher under dual- than under single-task conditions. Also, the effect on motor performance will be more pronounced and the effect on prefrontal activity will be less pronounced in old age. This age-dependency will be higher with the visual than with the verbal task.

Our behavioral data partly support the above expectations. Dual-task decrements were present and were higher in older than in young subjects, but only young adults showed significantly increased costs during our complex check condition. Though, a non-significant tendency to higher dual-task costs during the more complex task compared to the less complex task could be seen in older adults too. During dual-task walking, elderly subjects' step duration and step length decreased, their secondary task performance decreased and their number of steps

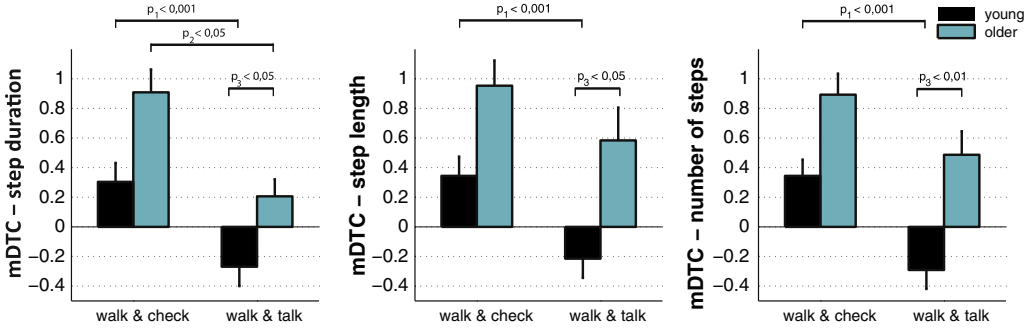

Fig. 2. Presentation of subjects' mean dual-task costs (mDTC) for (A) step duration, (B) step length and (C) number of steps separately for young and older subjects in two different dual-task walking conditions. Symbols represent the across-subject means of an age-group, error brackets show the pertinent standard errors. p_1 shows comparisons between *walk & talk* and *walk & check in* young adults, p_2 shows comparisons between *walk & talk* and *walk & check in* older adults, and p_3 displays comparisons between young adults and older adults in condition walk & talk. Only significant post-hoc results are displayed.

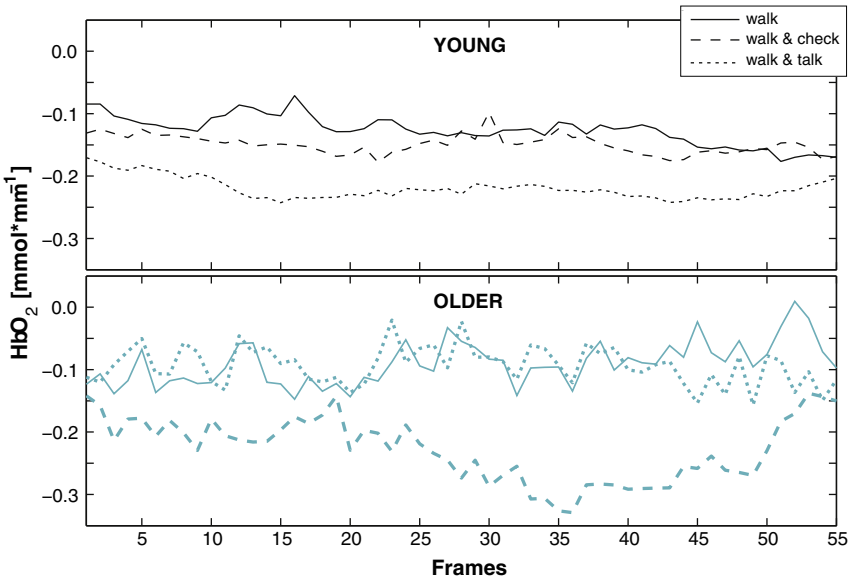

Fig. 3. Presentation of individual concentration changes in oxygenated (HbO_2) blood flow separated for one younger subject (displayed on top) and one older subjects (displayed at the bottom). Graphs are shown separately for all three walking conditions.

increased. These changes result in generally higher dual-task costs in the older group. To some extent, our findings confirm earlier studies, which unanimously observed that age-related deficits of dual-task walking are most dramatic with a visual secondary task (Li et al., 2001; Beurskens and Bock, 2011; Bock, 2008; Bock and Beurskens, 2011). Dual-task costs in the more complex task tend to be higher in older adults compared to young adults and compared to the less complex spelling task. Admittedly, post-hoc tests did not reach significance. In fact, young subjects had negative mDTC in condition *walk & talk*, which suggests that they actually improved performance during dual-task walking. This finding is typically attributed to synergy effects between two concurrent tasks (Hockey and Sauer, 1996). Similar findings have been found in postural stability tasks, were postural sway decreased and stability increased in dual-task situations (Stoffregen et al., 2000). Synergy effects are attributable to specific cognitive interference tasks that add benefit to both concurrently performed tasks. For example, during the simultaneous performance of a posture task and an additional observation task, postural sway was reduced, indicating that a stable posture is necessary to manage the secondary task (Stoffregen et al., 2000). In our study, young subjects might benefit from a joint rhythm during *walk & talk*, matching verbal answers and steps. Note, that the verbal WWT task more closely resembles the gait rhythm of young subjects in a way that one step includes two verbal answers (i.e., steps/s. = 1.65; letters/s. = 0.82; steps/letters ratio: 2.01). This joint rhythm was not feasible during *walk & check* because the checking task adds a visual and a motor component and addresses the same cognitive resources than walking. Although participants walked on a treadmill, compared to walking overground in previous studies, there is a tendency of increased dual-task costs during visually demanding dual-task situations, but the decrements are less pronounced when walking on a treadmill compared to walking on overground surfaces.

Our fNIRS findings clearly violate our expectations. We observed little change of prefrontal activation when contrasting dual- and single-task walking in young individuals for both, verbally and visually demanding dual-tasks. This indicates that, on behavioral level, our findings of negative mDTC in young adults do not seem to be associated with a change in neural activation patterns in their prefrontal brain area. Contrasts in older subjects yielded a change only for one of the two dual-task conditions and the change was contrary to our expectation, i.e., a decrease rather than an increase of activity under dual-task conditions. Dual-task costs in temporal gait measures (i.e., step duration) increased with increasing task complexity, but correlation analyses only revealed weak associations between increased costs and decreased neural activity. Our fNIRS results show a higher activation level in the younger group compared to older subjects, but only during visually demanding dual-task walking. Comparable to Holtzers' work, our elderly subjects maintained their prefrontal activity during the less complex *walk & talk* condition, and decreased their activity during the more complex *walk & talk* condition compared to single-task walking. While a lack of change could be attributed to low sensitivity of our fNIRS data, the decrease observed for *walk & check* argues against such a methodological flaw, and rather suggests that fNIRS is well suited to capture the waxing and waning of brain activity.

Our observation, that the most demanding experimental situation – *walk & check* – was accompanied by the lowest brain activity in seniors, fits commonly accepted models on cognitive information processing. Previous studies were able to show an age-related reduction in blood flow and a decrease in activation levels in prefrontal brain regions when the cognitive load was increased (Gur et al., 1987; Hazlett et al., 1998). Furthermore, several studies found these patterns of neural de-activation in memory and executive processing tasks (Nyberg et al., 2003; Johnson et al., 2004). Similar observations have been found in an imaging study by Zwergal et al. (2012), who showed reduced activation in motion-sensitive neural networks (e.g., visual and vestibular cortices) during more complex locomotion tasks. Activation in older adults decreased from standing to walking to running. In our study, older adults declined their neural activity with increasing task demand. The aforementioned CRUNCH-model by Reuter-Lorenz is well-suited to predict this phenomenon (Reuter-Lorenz and Cappell, 2008): with increasing task demand, older adults might reach a resource ceiling and therefore shift processing partly from the primary to an alternative brain network, thus effectively under-activating the former (Reuter-Lorenz and Lustig, 2005) and activating the latter networks (Stern, 2002). According to Stern's cognitive reserve theory (Stern, 2009), older adults might use a completely different set of brain networks than younger adults. Alternatively, they might continue using the same network with lower intensity and additionally recruit new networks not used by younger adults. Due to our optode array placement, we only observed the de-activation of prefrontal areas but were unable to detect the postulated activation of other areas. Additional substance for our findings can be gathered from a recent study on older adults' individual motor performance capacities. Older adults accomplish

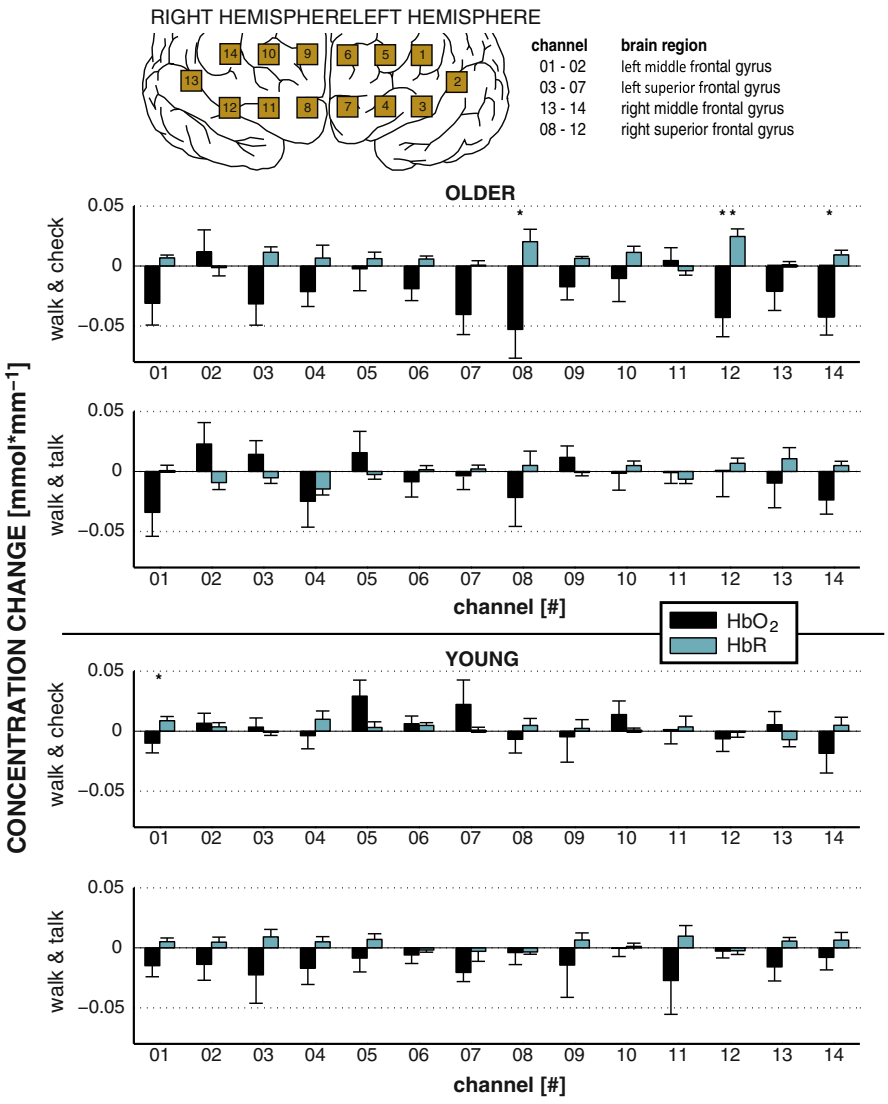

Fig. 4. Presentation of subjects' neural activation patterns separated for older and young subjects in our two conditions. In each division of the figure, the contrast between "*walk*" and "*walk & check*" is shown at the top and the contrasts between "*walk*" and "*walk & talk*" is shown at the bottom. Symbols represent the across-subject means, error brackets show the pertinent standard errors. For an overview, the top part of Fig. 4 shows a simplified representation of channel positions and the according brain regions. Asterisks represent channels with significantly reduced HbO_2 in young and older adults and for each condition ($^{*} = p < 0.05$ and $^{**} = p < 0.01$).

activities of daily living near their maximum capacity, indicating that relatively easy tasks require high efforts (Hortobagyi et al., 2003). This aspect might be a reference point for our study. Walking per se and especially walking while talking already puts older adults near their respective maximum capacity and a further increase in task demand (i.e., *walk & check*) causes them to shift their neural activation without increasing it in the first place. Compared to *walk & talk*, which is a less complex dual-task situation, the visually demanding and more complex *walk & check condition* puts higher demands to older adults processing capacities (Lindenberger et al., 2000; Bock, 2008). Walking is a visually demanding experience as we navigate through a visually defined space.

Table 3
Selected ANOVA outcomes: fNIRS measures.

	Oxygenated	De-oxygenated
Age	$F(1,22) = 0.83$ n.s.	$F(1,22) = 0.02$ n.s.
Condition	$F(1,22) = 0.04$ n.s.	$F(1,22) = 2.86$ n.s.
Age × condition	$F(1,22) = 5.57^{*}$	$F(1,22) = 4.54^{*}$
Channel	$F(13,286) = 1.03$ n.s.	$F(13,286) = 0.54$ n.s.
Age × Channel	$F(13,286) = 0.58$ n.s.	$F(13,286) = 1.66$ n.s.

n.s. and * indicate $p > 0.05$ and $p < 0.05$ respectively.

Thus, simultaneously performed visual tasks overstrain the older brain's executive system to coordinate navigation through this visually defined space and additional resources need to be recruited.

It still remains to be determined why young subjects in Holtzers' study (Holtzer et al., 2011) increased their prefrontal activation during *walk & talk* while our subjects did not change their neural activations. We attribute this to methodological differences in the study designs. The sampling duration was much shorter for Holtzers' registration, which makes direct comparison very difficult, particularly as activation during continuous tasks can be quite transient. In addition, subjects in our study walked on a treadmill while subjects in the study by Holtzer and colleagues walked on a pressure-sensitive floor on level ground. Hence, treadmill effects on walking performance of younger subjects could be observed (i.e., decreased dual-task walking speeds in Holtzers' study; better dual-task performance in our study), but further research is needed to better understand the contribution of treadmill vs. overground walking for different aspects of dual-task performance.

Correlations between prefrontal activation and locomotor performance on a subject-to-subject basis were poor in our study, except for one out of the 14 registered channels. It is interesting to note that this channel was located over the left Brodmann area 10 (i.e., the left

Superior Frontal Gyrus), a region associated with self-awareness and the processing of sensory feedback for the control of actions (Goldberg et al., 2006).

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.ijpsycho.2014.03.005.

References

Al-Yahya, E., et al., 2011. Cognitive motor interference while walking: a systematic review and meta-analysis. Neurosci. Biobehav. Rev. 35 (3), 715–728.

Beurskens, R., Bock, O., 2011. Role of motor skills and visual demand for age-related deficits in dual-task walking. Ageing Res. http://dx.doi.org/10.4081/ar.2011.e5.

Beurskens, R., Bock, O., 2012. The role of executive functions and memory in dual-task walking: a review. Neural Plast. 2012 (131608), 1–9.

Beurskens, R., Bock, O., 2013. Does the walking task matter? Influence of different walking conditions on dual-tasking in young and older persons. Hum. Mov. Sci. 32 (2013), 1456–1466.

Bock, O., 2008. Dual-task costs while walking increase in old age for some, but not for other tasks: an experimental study of healthy young and elderly Persons. J. Neuroeng. Rehabil. 13 (5), 27–36.

Bock, O., Beurskens, R., 2010. Changes of locomotion in old age are not the same under laboratory and under real-life conditions. Gait Posture 32 (4), 645–649.

Bock, O., Beurskens, R., 2011. Age-related deficits of dual-task walking: role of foot vision. Gait Posture 33 (2), 190–194.

Cabeza, R., 2002. Hemispheric asymmetry reduction in older adults: the HAROLD model. Psychol. Aging 17 (1), 85–100.

Cope, M., et al., 1988. Methods of quantitating cerebral near infrared spectroscopy data. Adv. Exp. Med. Biol. 222, 183–189.

Goldberg, I.I., Harel, M., Malach, R., 2006. When the brain loses its self: prefrontal inactivation during sensorimotor processing. Neuron 50 (2), 329–339.

Gur, R., et al., 1987. Age and regional cerebral blood flow at rest and during cognitive activity. Arch. Gen. Psychiatry 44 (7), 617–621.

Harada, T., et al., 2009. Gait capacity affects cortical activation patterns related to speed control in the elderly. Exp. Brain Res. 193 (3), 445–454.

Hazlett, E.A., et al., 1998. Age-related shift in brain region activity during successful memory performance. Neurobiol. Aging 19 (5), 437–445.

Hockey, G.R., Sauer, J., 1996. Cognitive fatigue and complex decision making under prolonged isolation and confinement. Adv. Space Biol. Med. 5, 309–330.

Holtzer, R., et al., 2011. fNIRS study of walking and walking while talking in young and old individuals. J. Int. Neuropsychol. Soc. 16 (5), 877–889.

Hortobagyi, T., et al., 2003. Old adults perform activities of daily living near their maximal capabilities. J. Gerontol. A Biol. Sci. Med. Sci. 58 (5), M453–M460.

Jang, K.E., et al., 2009. Wavelet minimum description length detrending for near-infrared spectroscopy. J. Biomed. Opt. 14 (3), 034004.

Johnson, M.K., et al., 2004. An age-related deficit in prefrontal cortical function associated with refreshing information. Psychol. Sci. 15 (2), 127–132.

Klem, G.H., et al., 1999. The ten-twenty electrode system of the International Federation. The International Federation of Clinical Neurophysiology. Electroencephalogr. Clin. Neurophysiol. Suppl. 52, 3–6.

la Fougere, C., et al., 2010. Real versus imagined locomotion: a [18F]-FDG PET-fMRI comparison. Neuroimage 50 (4), 1589–1598.

Leff, D.R., et al., 2011. Assessment of the cerebral cortex during motor task behaviours in adults: a systematic review of functional near infrared spectroscopy (fNIRS) studies. Neuroimage 54 (4), 2922–2936.

Li, K.Z., et al., 2001. Walking while memorizing: age-related differences in compensatory behavior. Psychol. Sci. 12 (3), 230–237.

Lindenberger, U., Marsiske, M., Baltes, P.B., 2000. Memorizing while walking: increase in dual-task costs from young adulthood to old age. Psychol. Aging 15 (3), 417–436.

Loader, C., Sun, J., 1997. Robustness of tube formula based confidence bands. J. Comput. Graph. Stat. 6 (2), 242–250.

McDowd, J.M., 1986. The effects of age and extended practice on divided attention performance. J. Gerontol. 41 (6), 764–769.

Mills, P.M., Barrett, R.S., 2001. Swing phase mechanics of healthy young and elderly men. Hum. Mov. Sci. 20 (4–5), 427–446.

Miyai, I., et al., 2001. Cortical mapping of gait in humans: a near-infrared spectroscopic topography study. Neuroimage 14 (5), 1186–1192.

Newman, A.B., et al., 2006. Association of long-distance corridor walk performance with mortality, cardiovascular disease, mobility limitation, and disability. JAMA 295 (17), 2018–2026.

Nyberg, L., et al., 2003. Neural correlates of training-related memory improvement in adulthood and aging. Proc. Natl. Acad. Sci. U. S. A. 100 (23), 13728–13733.

Obrig, H., Villringer, A., 2003. Beyond the visible — imaging the human brain with light. J. Cereb. Blood Flow Metab. 23 (1), 1–18.

Personnier, P., et al., 2010. Temporal features of imagined locomotion in normal aging. Neurosci. Lett. 476 (3), 146–149.

Reuter-Lorenz, P., 2002. New visions of the aging mind and brain. Trends Cogn. Sci. 6 (9), 394.

Reuter-Lorenz, P.A., Cappell, K.A., 2008. Neurocognitive aging and the compensation hypothesis. Curr. Dir. Psychol. Sci. 17 (3), 177–182.

Reuter-Lorenz, P.A., Lustig, C., 2005. Brain aging: reorganizing discoveries about the aging mind. Curr. Opin. Neurobiol. 15 (2), 245–251.

Scholkmann, F., et al., 2010. How to detect and remove movement artifacts in near-infrared imaging using moving standard deviation and spline interpolation. Physiol. Meas. 31 (2010), 649–662.

Schrager, M.A., et al., 2008. The effects of age on medio-lateral stability during normal and narrow base walking. Gait Posture 28 (3), 466–471.

Singh, A.K., et al., 2005. Spatial registration of multichannel multi-subject fNIRS data to MNI space without MRI. Neuroimage 27 (4), 842–851.

Steffener, J., Stern, Y., 2012. Exploring the neural basis of cognitive reserve in aging. Biochim. Biophys. Acta 1822 (3), 467–473.

Stern, Y., 2002. What is cognitive reserve? Theory and research application of the reserve concept. J. Int. Neuropsychol. Soc. 8 (3), 448–460.

Stern, Y., 2009. Cognitive reserve. Neuropsychologia 47 (10), 2015–2028.

Stoffregen, T.A., et al., 2000. Modulating postural control to facilitate visual performance. Hum. Mov. Sci. 19 (2), 203–220.

Strangman, G., Boas, D.A., Sutton, J.P., 2002. Non-invasive neuroimaging using near-infrared light. Biol. Psychiatry 52 (7), 679–693.

Suzuki, M., et al., 2008. Activities in the frontal cortex and gait performance are modulated by preparation. An fNIRS study. Neuroimage 39 (2), 600–607.

Tak, S., et al., 2010. Quantification of CMRO2 without hypercapnia using simultaneous near-infrared spectroscopy and fMRI measurements. Phys. Med. Biol. 55, 3249–3269.

Talairach, J., Tournoux, P., 1988. Co-Planar Stereotaxic Atlas of the Human Brain: 3-D Proportional System — An Approach to Cerebral Imaging. Thieme-Stratton Corp., New York p. 122.

U'Ren, R.C., et al., 1990. The mental efficiency of the elderly person with type II diabetes mellitus. J. Am. Geriatr. Soc. 38 (5), 505–510.

Verghese, J., et al., 2007. Quantitative gait dysfunction and risk of cognitive decline and dementia. J. Neurol. Neurosurg. Psychiatry 78 (9), 929–935.

Verhaeghen, P., et al., 2003. Aging and dual-task performance: a meta-analysis. Psychol. Aging 18 (3), 443–460.

Villringer, A., et al., 1993. Near infrared spectroscopy (NIRS): a new tool to study hemodynamic changes during activation of brain function in human adults. Neurosci. Lett. 154 (1–2), 101–104.

Worsley, K.J., Friston, K.J., 1995. Analysis of fMRI time-series revisited — again. NeuroImage 2 (3), 173–181.

Ye, J.C., et al., 2009. NIRS-SPM: statistical parametric mapping for near-infrared spectroscopy. Neuroimage 44 (2), 428–447.

Zwergal, A., et al., 2012. Aging of human supraspinal locomotor and postural control in fMRI. Neurobiol. Aging 33 (6), 1073–1084.