Research Article
Volume 7:7, 2020
DOI: 10.37421/ijn.2020.7.381

International Journal of Neurorehabilitation

ISSN: 2376-0281 Open Access

Eye Movements and Frontal Cerebral Blood Flow during Dual-Task Performance in Young Adults: Basic Data to Identify the Mechanisms Underlying Falling in Older Adults

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Abstract

This study aimed to obtain basic data necessary for elucidating the mechanisms underlying falling in elderly people during walking. The participants, who were healthy young women (n=19; mean age, 23.1 ± 1.9 years), performed pseudo-walking foot-stepping motions according to the following three conditions: (1) foot-stepping at their usual walking speed (single task), (2) performing a foot-stepping motion at their usual walking speed while solving a mathematical problem (dual task), and (3) performing foot-stepping at their usual walking speed while looking carefully at an image in front of them (control task). Participants' eyeball movements, number of steps, and blood flow rates in the frontal lobe were measured. We found that participants' eyeball movements were significantly larger and faster during the dual task than during the single or control task ($p<0.05$). There were no significant differences in the number of footsteps among the single, dual, and control tasks. Blood flow rates in the frontal lobe were lower for the dual task than for the single task. Collectively, these findings imply that an increase in eye movements during thinking in young adults may suppress the input of visual information, and this may be more pronounced in older people with relatively poor frontal lobe function. The results of this study provide a baseline to compare the results of a similar study performed in older individuals.

Keywords: Falling • Eye movements • Dual-task performance • Foot-stepping motion

Introduction

Falls are one of the primary risk factors that cause older adults to become bedridden. According to the Comprehensive Survey of Living Conditions conducted by the Japanese Ministry of Health, Labor and Welfare in 1998, falls and fractures are the third leading cause of patients becoming bedridden, culminating in the need for long-term care [1].

Conventional fall prevention methods target physical motor functions and involve methods for improving lower extremity muscle strength and body balance in individuals at a high risk of falling. Several reports have documented a decrease in the fall rate with the improvement of physical motor functions [2-4]. However, the fall-induced death rate in Japan was 5.3% (2005) in a population of 100,000 people, which has increased to 6.4% (2015) in the past 10 years. As the population of older individuals is continuously increasing, the incidence of falls, particularly those that result in death, will likely increase [5]. This suggests that the fall prevention strategies that have been implemented to date are inadequate.

While walking, individuals register and utilize visual information about the surrounding environment to prevent them from stumbling or colliding with objects. Attention is the extraction of specific information from various objects and experiences and the ability to be conscious of it clearly [6]. Several cognitive functions, including attention, are governed by the frontal lobe, which is the brain region most affected by aging [7]. Recent reports have indicated the role of frontal lobe activity in the act of walking. For instance, the gait may become unstable or slow down, or the individual may halt while simultaneously performing cognitive tasks such as calculations and word recall [8-11]. The distribution of attention resources by frontal association areas reportedly accounts for these observations. Attention allocation is limited in its capacity to process information simultaneously. When actions such as walking and thinking or operating a smartphone are performed concurrently, attention resources are allocated as necessary [12,13]. Aging is accompanied by a concomitant decrease in attention resources. Consequently, it becomes difficult for attention resources to meet the demands of multitasking [14,15]. Thus, if forced to pay attention to cognitive tasks during walking, the brain will allocate less attention to gait, thus affecting the act of walking.

Eye movement facilitates the acquisition of visual information, which is necessary for unimpeded walking, and the gaze is normally directed toward potentially hazardous objects. Performing other tasks while walking may diminish the visual attention necessary for walking and is strongly associated with falling while walking, the incidence of which is reportedly the highest among the older adults [11-18]. However, few studies have been conducted on the relationship between eye movements and frontal lobe function in older individuals. We previously investigated the differences in eye movements observed while walking and while simultaneously performing other tasks when walking [19]. However, we did not investigate the difference in frontal lobe function in that study. Therefore, the purpose of this study was to obtain basic data necessary for elucidating the mechanisms underlying falling during walking in elderly people. Specifically, we investigated eye movement and frontal lobe function in young adults while they simultaneously performed pseudo-walking foot-stepping motions and cognitive tasks.

Materials and Methods

We recruited 19 healthy young women (mean age: 23.1 ± 1.9 years) as volunteers, all of whom had no vision difficulties in everyday life and demonstrated a binocular visual acuity of at least 0.7 using the naked eye, contact lenses, or eyeglasses, as proven by the possession of a driver's license. We included only women in the study because they have been

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Received 20 October, 2020; **Accepted** 02 November, 2020; **Published** 09 November, 2020

shown to have a higher incidence of falling than men [20-22]. All participants were informed about the purpose of this study in advance, verbally and in writing, and written consent was obtained from each participant. This research was conducted with the approval of the Seijoh University Research Ethics Committee (2016 C0024).

Participants performed pseudo-walking foot-stepping motions, without moving their faces, while observing images projected on a screen placed 2 m in front of them. Participants were instructed to perform the following three tasks: (1) perform foot-stepping motions at their usual walking speed (single task), (2) perform foot-stepping motions at their usual walking speed while solving a mathematical problem while (dual task), and (3) perform foot-stepping motions at their usual walking speed while carefully looking at an image in front of them (control task). The control task in the single task was assumed to be a positive control for the participant consciously observing of the screen The control task in the dual task was assumed to be a negative control for the participant consciously observing of the screen. The aim of the control task was to confirm eyeball movement while the participant was consciously observing the screen.

Participants' eye movements and number of steps were measured simultaneously under the three conditions. The measurement protocol consisted of 1 cycle of 15-s practice, 30 s of rest, and 30 s of the task (Figure 1). To prevent participants from being aware of “seeing,” single tasks, dual tasks, and control tasks were performed in this order. There was ample rest time between tasks. The images displayed on the screen were recorded with a video camera at the eye level while an individual walked straight across the room at a rate of 1.4 m/s, which is the average walking speed of an adult. Each participant was instructed to perform the task while watching the image, as though she was walking through the room. The researchers recorded the video before the start of the experiment and used the same video for all participants.

For the dual task, we asked the participants to multiply a two-digit number with a single-digit number while performing foot-stepping motions. This calculation, which was regarded as a working-memory task by a previous study, recruits typical working memory, that is, the information necessary for the calculation is temporarily stored for its completion [23]. In our task, as the participants started the foot-stepping motion, the examiner orally presented questions, and the participants were required to perform the calculations repeatedly until they arrived at the correct answer. The examiner was positioned behind the participant so as not to visually distract the participant.

The eyeball movements were measured at a sampling rate of 30 Hz using an eye movement measurement system (TalkEye Lite, Takei Scientific Instruments Co., Ltd, Niigata, Japan) for all tasks. TalkEye Lite is a goggle-type eye-movement measurement system that processes pupillary images with the following settings: the wavelength of the detection light was 870 nm; the detection range was 50˚ to the left, 50˚ to the right, 20˚ upwards, and 20˚ downwards; the detection resolution was 0.1˚ (≤±20˚) and 0.5˚ for the whole area; and the detection error was 1˚ or less (≤±20˚), 2˚ or less (≤±40˚), and 3˚ or less for the entire area. The combined motion angle for both eyes in each task was measured, and the maximum eye displacement angle in the vertical direction (the sum of the angles at which the eyeball was displaced furthest upward and downward during a measurement lasting 30s) and lateral direction (the sum of the angles at which the eyeball was displaced furthest to the left and right during a measurement lasting 30s) was obtained. Further, the angle of eye movement per second in the vertical direction (the vertical eye movement speed) and lateral direction (the lateral eye movement speed) were obtained, and the mean values were calculated.

The number of footsteps was measured using a counting device (H-102, AS ONE Corporation, Osaka, Japan), and the average value was calculated.

The blood flow rate of the frontal lobe was measured using optical encephalography (OEG-16, Spectratech Inc., Tokyo, Japan). This device is widely used to measure cerebral blood flow in desktop tasks. In this study, participants performed a foot-stepping motion in place, which did not affect the measurements. Light was emitted via six two-wavelength embedded light-emitting diodes (wavelength 1: 840 nm, wavelength 2: 770 nm), light was received through six Si PIN photodiodes, the device featured 16 simultaneous measurement channels, and the distance between the light-emitting and receiving components was 3 cm in the OEG-16 specifications. We measured the amount of oxyhemoglobin in the prefrontal area, including the dorsolateral prefrontal cortex, through channels 1 to 16, in both the single and dual tasks. The experimental protocol for measuring the frontal lobe blood flow rate was a block design consisting of 3 cycles of 30-s tasks (dual task or control task) and 30s of rest single task (Figure 2). The reason was to confirm the attentional state during the dual task. Therefore, two trials were implemented under three conditions. The tasks were performed in random order. There was ample rest time between cycles. The differences between the amount of oxyhemoglobin detected during the task and at rest were calculated and averaged.

All values are presented as the mean ± standard deviation. In the data analysis, the maximum eye displacement angle in the vertical and lateral directions, the eye movement speeds in the vertical and lateral direction, and the number of footsteps were subjected to one-way repeated measures analysis of variance and Bonferroni's multiple comparison tests between groups. Data were analysed using SPSS version 24.0 (IBM Corporation, Chicago, IL, USA). The significance level was set at $p<0.05$. The changes in the amount of oxyhemoglobin were converted to Z-scores for comparison.

Results

There was no significant difference in the maximum vertical or lateral eye displacement angle between the single task (30.9 ± 17.7° and 34.1 ± 19.3˚, respectively) and control task (30.3 ± 17.5˚ and 34.9 ± 22.4˚, respectively). But the maximum vertical and lateral eye displacement angles were significantly larger during the dual task (51.3 ± 23.6˚ and 55.7 ± 23.0˚, respectively) than during the single or control task ($p<0.01$) (Figure 3). Also, there was no significant difference in the vertical or lateral eye movement speed between the single task (15.5 ± 7.5˚/s and 20.1 ± 9.1˚/s; respectively) and control task (14.0 ± 5.0˚/s and 21.3 ± 8.3˚/s, respectively). But the vertical and lateral eye movement speeds were significantly faster during the dual task (23.9 ± 9.8˚/s and 27.1 ± 9.7˚/s, respectively) than during the single or control task ($p<0.05$) (Figure 4).

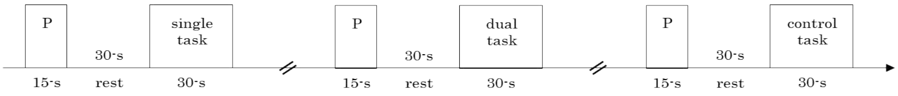

Figure 1. Measurement protocol for eyeball movements and number of steps.

Note: Single task, dual task, and control task were performed in this order. There was ample test time between tasks.

Abbreviation: P-Practice

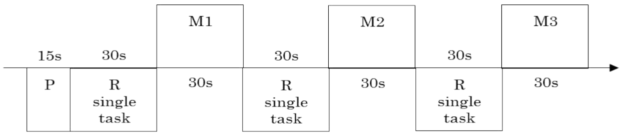

Figure 2. Measurement protocol for frontal lobe blood flow rates.

Note: A block design consisting of 3 cycles of 30-s tasks (dual task or control task) and 30s of rest (single task). The tasks were performed in a random order.

Abbreviation: P: Practice; R-Rest; M1: 1st Measurement; M2: 2nd Measurement; M3: 3rd Measurement

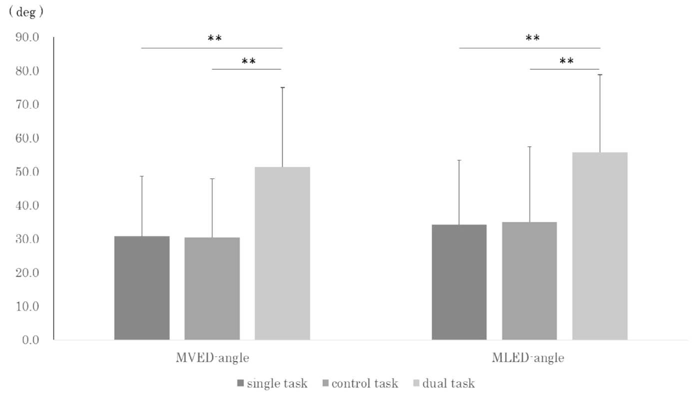

Figure 3. Comparison of the maximum vertical or lateral eye displacement angles among the single control and dual tasks.

Note: One-way repeated measures analysis of variance and Bonferroni's multiple comparison tests. Error bars show the standard deviation from the mean values.

**p<0.01 significant difference for single or control tasks vs dual task.

Abbreviation: MVED-angle: Maximum Vertical Eye Displacement Angles; MLED: Maximum Lateral Eye Displacement Angles

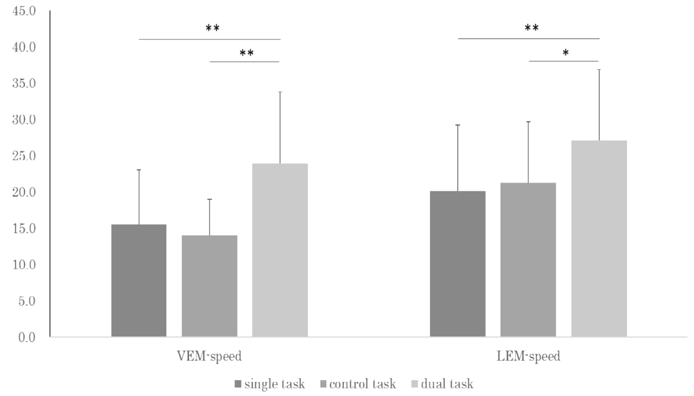

Figure 4. Comparison of vertical or lateral eye displacement speed among the single control and dual tasks.

Note: One-way repeated measures analysis of variance and Bonferroni's multiple comparison tests. Error bars show the standard deviation from the mean values.

*p<0.05, **p<0.01 significant difference for single or control tasks vs dual task.

Abbreviation: VEM-speed: Vertical Eye movement Speed; LEM: Lateral Eye Movement Speed

No significant differences in the number of footsteps were identified among the single (50.9 ± 4.1 steps), dual (50.3 ± 4.6 steps), and control tasks (50.6 ± 5.1 steps).

The amount of oxyhemoglobin measured (Z-score) was smaller for the dual task (-2.82 ± 9.34) than for the single task (2.51 ± 6.25). Moreover, several participants were unable to answer the mathematical problem correctly in the dual task; more than 60% of the participants replied that the calculation was too difficult or confusing.

Discussion

In a previous study [19], we compared eye movements in young adults who walked for 3 m without performing calculations (single-task walking) and while performing calculations (dual-task walking). We discovered that the maximum eye displacement angle was significantly larger and the eye movement speed was significantly faster during dual-task walking. In the present study, eyeball movements were measured using a pseudo-walking foot-stepping motion. In the control task, the maximum eye displacement angle was small, and no significant differences were observed between the single and dual tasks. This suggests that participants were carefully looking ahead during the single task. Moreover, since the eye movement speed necessary for gazing did not differ between the single and control tasks, the eye movement speed necessary for gazing was considered to be 14–15°/s. However, the dual task yielded significantly larger maximum eye displacement angles and faster eye movement speeds than did the single and control tasks.

Eye movements are influenced by the vestibulo-ocular reflex, and the eyeballs move in a direction opposite to that of head movement [24,25]. Herein, we controlled for head movement by instructing the participants to perform the foot-stepping motion while observing the image on the screen in front of them, without moving their heads during any of the tasks. Therefore, the influence of the vestibulo-ocular reflex on eyeball movement was likely negligible; the increased maximum eye displacement angle and eye movement speed that was observed in the dual task may be attributed to the calculations the participants were instructed to perform. Shima et al. [26] reported that even young people have a difficult time allocating attentional resources required to accomplish a highly complex dual task, noting that their task processing ability decreases. The mathematical problem posed to the participants in the present study consisted of the multiplication of a two-digit number with a one-digit number, which is a difficult working memory task irrespective of age or health status. However, since such calculations may have resulted in increased eye movements during the dual task, caution must be exercised when employing multiplication tasks in similar future studies.

The blood flow in the frontal lobe measured using functional near-infrared spectroscopy is used to determine activation of the frontal lobe, particularly the dorsolateral prefrontal cortex, as a correlate of the distribution in attentional resources. We hypothesized that the changes in oxyhemoglobin (Z-score) would increase in the dual task relative to the single task, but the changes in oxyhemoglobin were lower than expected. As the degree of difficulty of a cognitive task increases, frontal lobe activity reportedly increases. However, if the task is too difficult, working memory is overwhelmed, and activation of the dorsolateral prefrontal cortex is reduced [27,28]. Since the amount of oxyhemoglobin measured was smaller for the dual task than for the single task, it can thus be inferred that the calculation task used in the present study was too challenging.

Eyeball movements made during complex tasks are generally not used to gaze at an object. Rather, the eye engages in saccades, whereby the eye moves quickly and intermittently between fixation points [24]. A prior study demonstrated that when the line of sight is consistently directed towards an object of interest, it diminishes the occurrence of saccades and improves attention [29]. Here, we found that eyeball movements observed during the dual task were considerably larger and faster than those observed during the single and control tasks, thus reflecting a permanent departure from a forward gaze. As an image observed during a saccade is blocked by saccadic suppression, the increase in saccades that we noted during the dual task indicates that sufficient visual information was not acquired by the participants [30]. As such, the participants' attention toward the screen was diminished because they were concentrating on the calculation. It is also possible that the decrease in visual information processing caused by the reduced attention to the screen might have reduced blood flow to the frontal lobe; further study is needed to validate this conclusion.

Prior research in older adults has shown that calculations performed during walking decrease walking speed [10,11]. However, our results indicated that the performing calculations did not influence the number of steps taken by young adults. The relative ease of the foot-stepping motion, along with the presence of uncompromised frontal lobe function and sufficient lower extremity muscle strength and physical balance at a young age may account for the discrepant findings between studies.

The results of this study strongly suggest that as the amount of visual information decreases, young adults are unable to maintain a forward gaze while walking and performing another task. Walking is strongly related to frontal cortical activity, and the decline in frontal lobe function affects the ability to visually process information. It is therefore necessary to investigate the relationship between eye movement and frontal lobe function to elucidate the factors that promote falling among older individuals.

A limitation of this study was the use of a short connection cable for functional near-infrared spectroscopy, which made it impossible to collect data during actual walking. Thus, it is necessary to consider an appropriate measurement method for obtaining data during walking.

Conclusion

The prefrontal cortex is crucial for adequately allocating attention to each task while performing multiple actions simultaneously, such as thinking or talking while walking. This study showed that eye movements generated during the performance of dual tasks, even when one of the tasks is foot stepping, are larger and faster than those exhibited during the performance of a single task, indicating an increase in the allocation of attention to cognitive tasks and a decrease in the allocation of attention to the visual field. Thus, an increase in eye movements made by young adults during thinking may suppress the input of visual information. This tendency may become more prominent in older adults with relatively poor frontal lobe function. The results of this study provide a baseline to compare with the results of a similar study performed in older individuals.

Acknowledgments

We would like to express our gratitude to all the individuals who participated in this research.

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How to cite this article: Yamada K., Furukawa K, Yokoyama S, Kimura D, Watanabe K, "Eye Movements and Frontal Cerebral Blood Flow during Dual-Task Performance in Young Adults: Basic Data to Identify the Mechanisms Underlying Falling in Older Adults". Int J NeurorehabilitationEng 7 (2020) doi: 10.37421/ijn.2020.7.381