Relationships between footedness and executive function in upper-middle-aged people:
Evidence from the Yakumo Study

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中高年者のきき足の違いとバランスおよび実行系機能との関係について—八雲研究資料から—

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要約

本研究の目的は、健康な中高年の住民を対象に、実行系機能とバランス機能にきき足による違いがあるかどうかを検討することであった。実行機能テストとして Timed-Up-And-Go（TGUG）テストが採用され、バランス機能テストとして重心動揺計の指標（Romberg 比）が用いられた。調査対象群は、左足きき 32 人と右足きき 200 人であった。結果は、重心動揺計での Romberg 比の成績には左きき足群と右きき足群の間に違いが認められなかった。 しかし、TGUG テストでは、左きき足群の方が右きき足群よりも成績が有意に劣ることが明らかとなった。これらの結果は、前頭前野が実行機能を制御していることから、左きき足の中高齢者は右足ききの高齢者よりも実行機能が脆弱であるという仮説を支持している。

Key words
footedness difference, stabilometric balance function, Get-Up-and-Go (TGUG) test, prefrontal cortex function, upper-middle-aged people

1. Introduction

There are far fewer studies on footedness than on handedness (Elias & Bryden, 1998; Elias et al., 1998; Grouis et al., 2002; Tran et al., 2014; Tran & Voracek, 2016). This might partly be due to the large variety of upper limb functions and the magnitude of their influence on human behavior. Footedness is less susceptible to influence by environmental factors (e.g., writing habits and religious disqualification) than handedness, which means that the conditions are better for examining the original human physical function controlled by the brain (Packheiser et al., 2020a; 2020b; Peters, 1988; Tran & Voracek, 2016). Although there have been exceptional cases reported within the expansive literature on handedness, most articles report that there are differences in the executive functions of left-handed people compared to right-handed people, namely in various facets of cognitive function (Brandler & Paracchini, 2014; Corballis, 2021; Elias et al., 1998; Hugdahl & Davidson, 2003; McManus, 2002).

Two early works by Jorgenson et al. (1980) and Simon et al. (1985) reported on the administration of the Stroop color word test (SCWT) to left- and right-handed people as a measure of executive function. Both studies found that the performance of right-handed people was superior to that of left-handed people. In contrast, Beratis et al. (2010; 2013) compared the executive function of left- and right-handers with the Trail Making Test (TMT) and reported that right-handers performed less well than left-handers. Furthermore, Van der Elst et al. (2008) claimed that there was no significant difference due to handedness in the executive function assessed using the SCWT. These discrepancies may be due to the cognitive tasks used or the age or intelligence levels of the participants in these studies. Nevertheless, the relationship between executive function and handedness remains unclear.

In this context, Hatta (2016) administered the SCWT to 100 left-handers aged in their sixties (half were men and half were women) and 100 age-matched right-handers. The results failed to show any significant difference in either the color naming speed or the Stroop interference effect size. Hatta (2018) also examined the relationship between handedness and executive function in elderly people through the use of the digit cancellation test (D-CAT); that study included 76 left-handers and 76 age-matched right-handers. Visuospatial performance was also examined using the Money Road-Map Test. Left-handers exhibited poorer performance on both tests than right-handers. Right-handed people showed a typical laterality with regard to the relationship between sex and facets of cognition, whereas left-handed people showed no clear laterality difference. Hatta et al. (2020) further examined handedness differences in cognitive aging by comparing the performance decline ratios of 22 middle-aged left-handers and 78 middle-aged right-handers. The performance decline ratios were calculated individually using longitudinal data with a 10-year interval. The results indicated that the performance decline ratio in left-handers was significantly larger than that in right-handers, both in single-digit and three-digit cancellation tasks. This suggests a low aging tolerance of executive function, especially in the information updating and shifting components of the three executive function components (Miyake et al., 2000). From these findings, we proposed the possibility that elderly left-handers are more vulnerable in terms of their executive function than elderly right-handers. This proposal is the reverse of that presented by Beratis et al. (2010; 2013).

The APA Dictionary of Psychology (VandenBos, 2015) describes executive function as follows: “higher level cognitive processes of planning, decision making, problem solving, action sequencing, task assignment and organization, effortful and persistent goal pursuit, inhibition of competing impulses, flexibility in goal selection, and goal-conflict resolution. They are frequently associated with neural networks that include the frontal lobe, particularly the prefrontal cortex.” Deficits in executive functioning are seen in various disorders (e.g., Alzheimer’s disease); therefore, understanding this function is vital when examining cognitive aging effects. The concept of executive function, which was introduced by Baddeley (2012), has become an important concept in the field of cognitive psychology, partly because of its comprehensiveness. It seems that this concept has also found use in the field of rehabilitation and orthopedic medicine, where the concept of the executive system is considered to include the initiation and execution of physical human behavior in everyday life.

In cognitive psychological studies, the SCWT and TMT are considered superior tools for measuring executive function; however, in rehabilitation and orthopedic medicine, the Timed Get-Up-and-Go (TGUG) test is regarded as one of the best tests for measuring executive functions related to daily life (Blackwood et al., 2016; Donoghue et al., 2012; Kose et al., 2016; Langeard et al., 2017). A major feature of the TGUG test is that it incorporates a series of tasks: standing up from a seated position, walking, turning, stopping, and sitting down, all of which are critical for independent mobility.

In sum, the purpose of this study was to examine our hypothesis that left-footed (but not left-handed) people are vulnerable in terms of the executive functions measured using the TGUG test. As Miyake et al. (2000) discussed, the execution function is assumed to be the most important element in the process of planning to perform daily human behaviors. The TGUG test is used to measure the executive system that reflect prefrontal function. Whereas the upright balancing task is less dependent on prefrontal lobe function. Here, it is necessary to clarify the difference between the TGUG test and the SCWT and TMT, though intuitively. The TGUG test reflects not only a decision made by the brain network, but also the related whole body physical movements. In contrast, the SCWT and TMT mainly measure the decision made by the brain network. Even in the SCWT and TMT, finger movement and verbal response use the locomotorium; however, the TGUG test is the only test that includes tasks that reflect full body locomotorium activity.

Based upon our previous findings concerning handedness difference in vulnerability of prefrontal function in the elderly, the working hypotheses of this study were: (1) that left-footed people perform worse than right-footed people in the TGUG test, and (2) that there is no difference in the performance of left-footed people and right-footed people in the balancing task.

2. Method

2.1 Participants

The study population consisted of 200 right-footed people and 32 left-footed people. The participants were selected from those who had joined the Yakumo Study health examination conducted in 2014. The right-footed group (aged 40-92 years) consisted of 112 women and 88 men. The left-footed group (aged 40-80 years) consisted of 17 women and 15 men. The mean ages of the right-footed men and women were 63.64 (SD = 9.79) and 61.45 years (SD = 10.42), respectively. The mean ages of the left-footed men and women were 67.67 (SD = 6.93) and 60.88 years (SD = 9.00), respectively. All participants were physically and cognitively healthy.

2.2 Footedness

According to the Step on Stool Test procedure of Chapman et al. (1987), when climbing a wooden platform with a height of 40 cm, the foot on the side where the first step was taken was used as the dominant foot. Two Yakumo Study Orthopedics Group staff members confirmed the operation. There are several proposals for the “preferred foot” test, such as the Waterloo footedness test, in which 12 items are used for factors related to footedness (Elias et al., 1998). However, Schneiders et al. (2010) and Yoshida et al. (2014) suggested that using only one preference behavior item was sufficient for determining foot dominance in bilateral mobilizing tasks (Van Melick et al., 2017). It might be considered a limitation of the present study that the dominant foot was not assessed using the standardized questionnaire test; however, we regard unconscious physical movement to be a more reliable measure than questionnaire tests, which might be influenced, or biased, by mental processes.

2.3 Balancing

The postural balancing function was measured using a stabilometer (Anima Co. Tokyo) in the manner described previously (Hatta et al., 2005). The manual and standard norms for this stabilometer were developed by Tokita (1996). Two examiners, an orthopedic surgeon and an assistant, administered the postural examination to each participant. The stabilometer can provide indices, such as the distance and size of moving tracks for 60 s and the Romberg ratio. The Romberg ratio (ratio of the area of the center of gravity sway locus while standing with closed eye and open eye conditions) was employed. The Romberg ratio reflects the cerebello-thalamo-cortical circuit functions more directly than other indices, such as the velocity of moving (Hatta et al., 2005), and a large Romberg ratio indicates a weak balancing ability (Tokita, 1995). This measure has been employed as a useful tool for the diagnosis of Parkinson's disease and equilibrium disorders, and it relates to connectional profiles that are involved in "automatic" motor functions (Hagino, 2006; Ito, 2008; Mauritz et al., 1981; Njiokiktjien et al., 1978).

2.4 Executive function

The TGUG test was employed to measure executive function (Padsiadlo & Richardson, 1991; Wall et al., 2000). Each participant sat in a wooden chair with an upright backrest and, at the signal of the examiner, stood up from the chair, passed a landmark 3 m ahead at his or her usual walking pace, and then took time to sit back in the chair. The two examiners used a stopwatch to measure the time (s) required for each participant to complete the "getting up from the chair, walking, detouring, and sitting on the chair again" protocol. Each participant was measured twice. No auxiliary equipment was used during the movement. The time (s) required to complete this TGUG test was recorded as the executive function index.

3. Results

The mean Romberg ratios and TGUG test results of the right- and left-footed groups are shown in Table 1.

An analysis of variance (ANOVA) was conducted, with a one between (group: footedness) and one within (condition: Romberg ratio/TGUG test) mixed design. The results showed that both the main factors of group and condition were significant (F (1, 230) = 6.629, p = 0.011, F (1, 230) = 628.484, p = 0.000), and that the interaction between the factors was also significant (F (1, 230) = 5.646, p = 0.018). To clarify the interaction, further analyses were conducted. The results revealed that the left-footed people showed longer TGUG test times than the right-footed people (F (1, 460) = 12.250, p = 0.0005), while the comparison of the Romberg ratios of the left-footed and right-footed people did not show a significant difference (F (1,460) = 0.015, p = 0.902). These findings supported our working hypotheses: (1) that left-footed people perform less well (longer required time) than right-footed people in the TGUG test, and (2) that there is no difference in the performance of the balancing task by left-footed and right-footed people. Figure 1 shows the data that support these findings.

Table 1: Mean TGUG (Timed Get-Up-and-Go) performances (in second) and Romberg ratios in the right- and left-footers

	Right-footers (N = 232)	Left-footers (N = 200)
TGUG	6.300 (1.359)	7.39 (5.103)
Romberg ratio	1.289 (0.311)	1.327 (0.354)

Note: Standard deviations are shown in the parentheses.

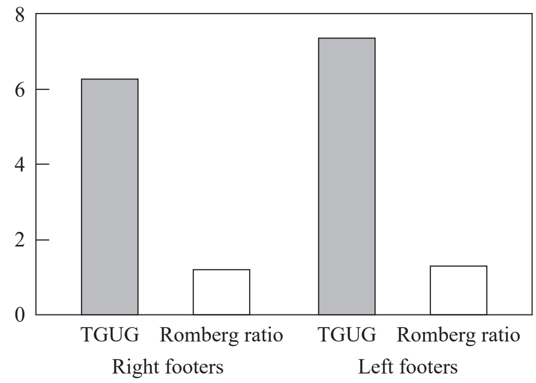

Figure 1: Mean performances in TGUG (Timed Get-Up-and-Go)

Note: Sec. in TGUG and Romberg ratio in the left and right-footers.

4. Discussion

Several studies have reported that the TGUG test is a reliable measure for assessing executive function, as well as the SCWT, TMT, and D-CAT. For example, Kose et al. (2000) found that performance on the TGUG test is strongly related to performance on the TMT but not to memory performance nor MMSE (Mini Mental State Examination). They also reported that TGUG test performance is associated with indicators of brain volume and severe medial temporal area atrophy among community-dwelling older adults with normal cognition or mild cognitive impairment. When reporting data from the Resources and Activities for Life-Long Independence (RALLI) Study, McGough et al. (2011) stated that TGUG test performance is related to executive function tasks, the SCWT, and the TMT, even after adjusting for age, sex, and age-related factors in sedentary adults with an MCI (Mild Cognitive Impairment). Donoghue et al. (2012) also reported that TGUG test performance is associated with executive function and performance on memory tests and information processing speed, based on The Irish Longitudinal Study on Aging (TILDA). Similarly, Blackwood et al. (2016) demonstrated that TGUG test performance is closely related to TMT performance and suggested that the TGUG test result is a useful index when MCI is suspected.

Before discussing the results, it is necessary to first confirm the relationship between the dominant foot and the dominant hand. Previc (1991) noted that the left-otolithic advantage in most humans underlies the reliance on the left side of the body for postural control, and on the right side for voluntary motor behavior. That is, when our human ancestors became bipedal instead of quadrupedal, the left foot was used to maintain balance or pivot their whole body, and the right hand was used to reach to pick up food while the left hand held onto a support, such as a tree branch. In bipedal behavior, right-handed people use the right foot in mobilizing tasks, such as kicking a pebble, and use the left foot to maintain balance (Corballis, 1989; Hatta & Koike, 1991; MacNeilage et al., 1987). Therefore, it is reasonable to consider both left-handed people and left-footed people as displaying atypical laterality.

The previously introduced studies (Beratis et al., 2010, 2013; Hatta, 2018; 2020; Jorgenson et al., 1980; Simon et al., 1985; Vander Elst et al., 2008) all examined the relationship between handedness and executive function. Therefore, to our knowledge, this is the first study to directly examine the relationship between footedness and executive function. As handedness and footedness can be regarded as very similar concepts, one may argue that the examination of footedness and executive function does not provide new and interesting information. However, as described earlier, footedness is less susceptible to environmental factors, such as writing habits and religious disqualification, than handedness, which means that footedness has desirable conditions for the examination of the original human physical function controlled by the brain (Packheiser et al., 2020).

The findings of this study are simple and clear: the performances of the left-footed people in the executive function task were worse than those of the right-footed people, and there was no difference due to footedness in the balancing task. This suggests that there is no difference due to footedness in the balancing function, which is low and basic in the human phylogenetic developmental hierarchy. However, the left-footed people performed relatively worse on the TGUG test, which involves developmentally higher-order planned movements. These findings seem to coincide with Previc's phylogenic explanation of the dominant hand and foot.

Considering the purpose of this study, the findings robustly showed that the executive function of left-footers is more vulnerable than that of right-footers. This proposal of vulnerability in terms of the executive function of the left-footers is coincident with the findings of our handedness studies (Hatta et al., 2018; 2020) and those of Jorgenson et al. (1985) and Simon et al. (1985). They are not, however, in accord with the findings of Beratis et al. (2010; 2013) and Vander Elst et al. (2008). The participants in Beratis et al.'s (2013) study were exceptionally talented college students, and their findings seem not to be generalizable. They relied on Geschwind's sex hormone theory, which states that a person with genetic information that favors right-handedness has slower development of the left part of the brain due to excessive secretion of male hormones during the fetal period, and that the target part of the right brain compensates by promoting growth (Geshwind & Galaburda, 1985). This promotion of posterior right brain growth and the resulting increase in asymmetry of the temporal plane can lead to some left-handers possessing special abilities (e.g., idiot savant with excellent intellectual abilities in mathematics or art). According to Beratis et al.'s rationale, the right brain of the left-hander is heavily involved in executive function, assuming that the development of the right brain is promoted and that executive function is also excellent due to the excessive secretion of androgen. However, as far as we know, no brain imaging study has demonstrated these special features in left-handers. Several studies with right-handers (left-handers were excluded) have shown that the right frontal lobe is more active than the left frontal lobe during the B-type task of the TMT in brain imaging using fMRI (functional Magnetic Resonance Imaging) and NIRS (Near-infrared spectroscopy) (Jacobson et al., 2011; Nakahachi et al., 2010). For example, Jacobson et al. (2011) reported greater activity of the right inferior / middle frontal cortices during the B-type task than during the A-type task.

Vander Elst et al. (2008) failed to demonstrate a handedness difference in executive task performance. Using the Maastricht Aging Study database, they evaluated the effect of handedness on age-related decline in four major cognitive domains: speed of information processing, verbal learning, long-term verbal memory, and executive functioning. The results failed to provide support for the hypothesis that left-handedness is associated with a more pronounced age-related cognitive decline in executive function tasks, such as those tested using the SCWT and the Letter Digit Substitution Test (LDST). As the authors themselves described in the text, the probable reason for failing to find a significant handedness difference is the six-year follow-up period (in the longest case). With a baseline age of 50 years, the six-year follow-up did not allow sufficient time for age-related changes in cognitive function to become apparent. It is worth noting that Hatta et al. (2020) demonstrated a significant handedness difference in age-related decline when they used the Yakumo Study database and a follow-up interval of 10 years for 56-year-old left-handers and 58-year-old right-handers. Their findings demonstrated that the performance decline ratio in the left-handers was significantly larger than that in the right-handers, suggestive of a low aging tolerance of executive function in elderly left-handers. It should also be noted that Vander Elst et al. (2008) used the SCWT and LDST as the execution test tasks, while Hatta et al. (2020) used the DLT (single- and three-digit cancellation) as an executive function task. Needless to say, it has been reported elsewhere that the D-CAT cognitive task can be used to address executive function (prefrontal cortex activation) (Hatta et al., 2012; Hibino et al., 2013).

The findings presented thus far can be summarized as follows: previous studies seem to support the view that ordinary left-handed people are more vulnerable in terms of executive function; our findings indicate that left-footed people are more vulnerable than right-footed people; and our findings coincide with those of handedness studies. The results of this study elicit the question: Why are left-footed people inferior to right-footed people in the execution system function, especially in the upper-middle-aged group? It is difficult to propose a simple explanation for why left-footers are inferior to right-footers in cognitive function. At present, it is reasonable to say that various factors contribute in a mixed fashion, such as the pathological left-handedness theory described below.

The pathological left-handedness theory claims that sinistrality is probabilistically related to minor deviations from neurological and cognitive norms (Coren & Halpern, 1991). The reserve theory suggests that the negative effects of aging on cognitive functioning are more pronounced in people who possess a smaller amount of reserve capacity due to minor abnormalities in their brain that are brought about by sex-related hormone secretion (Geshwind & Galaburda, 1985), birth stress (Bakan et al., 1973), a premature birth and low birth weight (Powls et al., 1996), and older age of the mother at the time of delivery (Coren, 1990).

With the rapid progress in brain imaging research methods that began in the 1970s, attempts have been made to examine the association between handedness and the organic and functional differences in the brain. In 2008, we reviewed studies that used brain imaging as an index and handedness as a variable and found that there are differences between right-handed and left-handed groups in both morphological imaging research and functional imaging research (Hatta, 2007; Hatta, 2008). For example, in MRI studies, the degree of asymmetry of the temporal plane related to language and the size of the corpus callosum are different between the two handedness groups, and in fMRI and PET studies, there are differences in the motor and auditory cortex. Differences were also found in the degree of brain activity. Numerous more recent reports also prove that differences exist. For example, even regarding the sense of smell, it has been reported that the emotional response to odor differs depending on the handedness of the smeller Royet et al. (2003). They reported a difference in the activation site between the left ventral insula for right-handers and the right ventral insula for left-handers. It has also been reported that there is a difference in the size of the amygdala by handedness: the right brain is larger in right-handers, and there is no difference in size between the left and right amygdala in left-handers (Monk, 2008; Omura et al., 2005).

In conclusion, based on the present behavioral measure findings and previous brain imaging studies, it seems reasonable to propose that left-footed people (left-handed) are more vulnerable than right-footed people (right-handed) in terms of the executive functions that reflect not only decisions made by the brain network but also those related to whole-body physical movement. A detailed explanation of the mechanisms responsible for the difference has yet to be determined.

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