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博士論文

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(視空間ワーキングメモリの低下を呈した症例における電子機器の数字入力操作)

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Numeric input operation on electronic devices among individuals with visuospatial working memory impairment

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ABSTRACT

Background: In human-computer interactions, higher-level visuospatial function is likely needed to effectively use the interface. The aim of this study is to clarify whether individuals with visuospatial defects can use electronic devices effectively.

Method: We quantitatively and qualitatively analyzed the ability of seven individuals with Bálint syndrome and seven individuals with left-unilateral spatial neglect (USN) to input a digit sequence into a flat touch interface. Control groups consisted of seven individuals with memory deficits and 11 healthy individuals.

Results: Participants with Bálint syndrome took longer and had more hesitations than the USN group and the two control groups to input numerical sequences (Steel-Dwass test, $p < 0.01$). In addition, participants with Bálint syndrome had a high percentage of hesitations for exploration of the button array on the interface relative to USN and the memory deficit group (Fisher's exact test, $p < 0.05$). Regarding neuropsychological data, participants with Bálint syndrome had a lower score for visuospatial working memory than participants with USN and the memory deficits control group (Steel-Dwass test, $p < 0.01$).

Conclusion: The results shed some light on the relation between visuospatial working memory deficits and the spatial perception of interface layouts and spatial control during electronic device operation.

Keywords: Electronic devices; Bálint syndrome; Unilateral spatial neglect; Visuospatial working memory impairment; Instrumental activities of daily living.

INTRODUCTION

Electronic devices have replaced many types of instrumentation, appliances, and other devices. Modern electronic devices require that a user carries out an operation involving a button while viewing the display (e.g., a personal computer, a smartphone, a cash dispenser, a ticket vending machine). In human-computer interactions, a visuospatial memory is necessary to search from a large number of information in navigation between various applications and documents (Tak, Scarr, Gutwin, & Cockburn, 2011). Additionally, a higher-level visuospatial knowledge of an interface layouts leads to efficient performance (Scarr, Cockburn, & Gutwin, 2013). Generally, to operate modern electronic devices, we must comprehend information across the entire interface and perform operations within a specified time period. The following situations can occur if there are long hesitations during the operation of these electronic devices. (1) The screen of a personal computer or a smartphone is blacked out. (2) The inserted card is returned from a cash dispenser. (3) The inserted money is returned from a ticket vending machine. During this process, it is necessary to match one's timing with the response timing of the device. Therefore, it is quite reasonable to assume that adequate visuospatial function is needed to comprehend the information of the interface.

Regarding visuospatial function, individuals with Bálint syndrome (Bálint, 1909) or unilateral spatial neglect (USN) bear all the characteristics of visuospatial deficits. The characteristic Bálint syndrome is categorized into three signs: psychic paralysis of gaze, spatial disorder of attention, and optic ataxia. Psychic paralysis of gaze is the inability to voluntarily shift one's gaze to objects of interest despite unrestricted ocular movement. Spatial disorder of attention is also known as dorsal simultaneous agnosia (Luria, 1958; Rizzo, & Vecera, 2002) and results in the in ability to perceive several items in a visual scene at any one time. Optic ataxia refers to a difficulty in reaching under visual guidance that occurs in the absence of any muscle weakness. In daily life, patients with Bálint syndrome have difficulties finding objects and remembering locations as well as spatial relationships between objects. Patients with USN often appear to be unaware of contralesional stimuli, a deficit that cannot be accounted for by deafferentation. It is thought that many symptoms of neglect are related to attention deficits (Heilman, Watson, & Valenstein, 1993). Left USN after a right hemispheric lesion is also more long-lasting and chronically affects activities of daily living (Ten Brink, Verwer, Biesbroek, Visser-Meily, & Nijboer, 2017; Spaccavento, Cellamare, Falcone, Loverre, & Nardulli, 2017).

Visuospatial deficits can occur as a result of not only acquired brain injury but also neurodegenerative disease. Posterior cortical atrophy (PCA) is the most frequent atypical presentation of Alzheimer disease and is characterized by a progressive impairment of higher-order visuospatial functions that occurs earlier and much more prominently within the disease progression than other cognitive disabilities such as memory and execution capacities (Benson, Davis, & Snyder, 1988). PCA patients present bilateral occipitoparietal damage and consistently develop Bálint-Holmes syndrome (Nestor, Caine, Fryer, Clarke, & Hodges, 2003; Pisella, Biotti, & Vighetto, 2015).

Studies that described difficulties in the operation of electronic devices by persons with visuospatial deficits have been reported. Denburg, Jones, & Tranel (2009) reported that a patient with Bálint syndrome displayed especially prominent simultanagnosia, as evidenced in her daily life (e.g., the inability to use a calculator or a telephone). Clavagnier, Fruhmann, Klockgether, Moskau, & Kamath (2006) also reported that a patient with simultanagnosia resulting from PCA deteriorated steadily with respect to her use of devices, such as using the phone. Nygård, & Starkhamma (2007) demonstrated that people with dementia have difficulty using electronic devices based on the Everyday Technology Use Questionnaire and suggested that visuospatial deficits may underlie some of these difficulties (e.g., an inability to turn handles and switches in the appropriate direction and to coordinate more than one piece of technological equipment). In short, these studies consisted of case studies and a questionnaire-based investigation, and none had assessed the abilities of individuals with acquired brain injury or neurodegenerative disease using the devices themselves. Therefore, we previously assessed the difficulties and the extended length of time needed to input numbers into a smartphone, a feature phone, and an electronic calculator among patients with Bálint syndrome (Sunagawa, Nakagawa, & Funayama, 2015). The smartphone had a flat touch interface, whereas the feature phone and the electronic calculator had buttons that protruded from the surface. These three different types of devices were used in case the shape or color of a device or the button type affected task performance. For all three devices, however, patients with Bálint syndrome took longer to input a digit sequence than control groups. Based on this finding, it is likely that an ascertainment of interface layouts and control locations is more important than haptic feedback. As it is predicted that the flat touch interface will become mainstream for electronic devices, we were prompted to investigate further the association between visuospatial function and operation of a flat touch interface.

The visual search is an important topic in examining the association between visuospatial function and modern electronic devices. With respect to dorsal simultanagnosia, patients with PCA show reduced deployment of attention over space (simultanagnosia), resulting in increased visual search times (Pisella et al., 2015). Furthermore, in the same study, several patients with PCA had ocular revisiting behavior that caused frequent omissions during visual searches. This revisiting behavior in spatial remapping has been ascribed to a deficit of visuospatial working memory (Bays, & Husain, 2007; Pisella et al., 2015). Rizzo, & Vecera (2002) reported that dorsal pathways involved in working memory for processing connect with dorsolateral areas involved mainly in working memory for spatial location. In addition, they also reported that impairments of working memory for objects and their locations could potentially contribute to the perceptual manifestations reported in Bálint syndrome. These previous studies used tasks that require visual searching and remembering locations. Additionally, it is thought that visuospatial working memory deficits influence these tasks. Regarding the operation of electronic devices with a touch interface, it is assumed that the tasks using flat touch interface were similar to those in the previous studies because visual searching and remembering locations are necessary for inputting a numerical sequence.

We had two primary aims in this study: (1) to examine that individuals with Bálint syndrome and USN require more time to use an interface with the specific number of buttons and (2) to investigate in detail the effects of Bálint syndrome and USN on the time required for numeric input. Our hypothesis was that study participants with Bálint syndrome and USN would take longer to input a digit sequence. We also hypothesized that visuospatial working memory deficits among participants with Bálint syndrome and USN would influence the time needed for numeric input operations. Accordingly, we assessed the ability of individuals with Bálint syndrome and USN to use a tablet-type device with a flat touch interface in comparison with the control groups.

For this study, we recruited two control groups, one composed of healthy participants and the other composed of individuals with cognitive dysfunction (i.e., memory deficits). The memory deficits group was included because we wanted to confirm that memory function does not affect the performance in the tasks of numeric input, and that visuospatial function is more important. Participants with memory deficits were expected to be able to complete the numeric input tasks because their visual, linguistic, praxic, and visuospatial functions are not impaired and the task requires a limited amount of memory function.

To operate electronic devices, individuals need several types of cognitive functions: visual, linguistic, praxic, executive, memory, and visuospatial. To enable a study to focus specifically on visuospatial function, tasks should take a small amount of time and be easy to understand and accomplish. A simple button-pressing task on an electronic device should be suitable for such a purpose because it requires a limited amount of cognitive function.

METHODS

Participants

This study was reviewed and approved by Kobe University Human Research Ethics Committee. This study was performed after obtaining informed consent from all subjects according to the Declaration of Helsinki.

Seven participants with Bálint syndrome were recruited from the Department of Rehabilitation at Edogawa Hospital (n = 2); the Cognitive Function Clinic at Ashikaga Red Cross Hospital (n = 2); the Department of Rehabilitation at Asakayama Hospital (n = 1); and Rashinban, a Community Workshop (n = 2). The etiology of Bálint syndrome was cerebrovascular disease for all participants. All study participants were medically stable and had passed the acute and subacute stages of brain damage within a few months of initial injury.

When participants were deemed medically stable, they had at least two of the following three symptoms: psychic paralysis of gaze, dorsal simultanagnosia, and optic ataxia. Participant 1 initially had all three symptoms when she became medically stable

~0.25 yr after brain damage. The psychic paralysis of gaze exhibited by Participant 1 had gradually resolved within 1 yr, and she had only two of the three symptoms (dorsal simultanagnosia and optic ataxia) at the time of our examination. Participant 2 initially had only two of the three symptoms (dorsal simultanagnosia and optic ataxia) after brain damage and when she was medically stable ~0.25 yr after brain damage. Participant 2 still had two symptoms at the time of our examination. These 2 participants were defined as having severe Bálint syndrome. Participants 3–7, defined as having mild Bálint syndrome, initially had only two of the three symptoms (dorsal simultanagnosia and optic ataxia) after brain damage and when they were medically stable ~0.25 yr after brain damage. Their symptoms had improved within 0.5 yr such that they had only dorsal simultanagnosia at the time of our examination. Thus, dorsal simultanagnosia, which is considered the hallmark of Bálint syndrome (Rizzo, & Vecera, 2002), was present in all seven participants. During our examination, for assessment of dorsal simultanagnosia, we followed the method of Rizzo, & Vecera (2002), for which a patient must have met all of the following criteria: (1) The patient indicates that stationary objects in the visual environment can disappear from their direct view. (2) The patient reports intermittent or fragmentary perception of the visual environment. (3) The patient is unable to make visual sense of the complete Boston Cookie Theft picture (Goodglass, & Kaplan, 1983). (4) The patient fails to properly count the number of dots in at least one of the three trials (consisting of three, four, and five dots in descending order) in the visual perception test for agnosia (Japan Society for Higher Brain Function, 1998).

Seven participants with left USN that was due to right hemisphere damage were recruited from Edogawa Hospital (n = 1); Ashikaga Red Cross Hospital (n = 2); Rashinban (n = 1); and Wakaba, a Community Activity Support Center (n = 3). The etiology of USN was cerebrovascular disease in six participants and traumatic brain injury in one participant. All study participants were medically stable and had passed the acute and subacute stages of brain damage within a few months of initial injury.

When participants were deemed medically stable, they scored below the cut-off on at least three of six conventional subtests of the Japanese version of the Behavioral Inattention Test (BIT) (BIT-J; Ishiai, 1999). In addition, they scored more than one point on at least one of 10 subtests of the Japanese version of the Catherine Bergego Scale (CBS-J; Nagayama, 2011) at the time of our examination. The CBS-J was filled out by guardians under the supervision of the therapist. The CBS was specifically developed by Bergego et al. (1995) and Azouvi (1996) to assess the presence of neglect in everyday life situations. It is a standardized checklist to be used by an occupational therapist to observe hemi-inattention with respect to 10 activities (e.g., grooming or shaving, dressing, eating). On this scale, the severity of neglect is rated from zero to three points for each item: 0 = no neglect, 1 = mild neglect, 2 = moderate neglect, and 3 = severe neglect.

For the memory deficits control group, seven participants with memory deficits were recruited from the Wakaba. The etiology of memory deficits was cerebrovascular disease for two participants, traumatic brain injury for two participants, and brain tumor for three participants. All study participants were medically stable and had passed the acute and subacute stages of brain damage within a few months. Their visual, linguistic, praxic, and visuospatial functions were not impaired, and they scored below the cut-off on the Japanese version of the Rivermead Behavioural Memory Test (RBMT) (Watanuki, Hara, Miyamori, & Etoh, 2002) at the time of our examination. Eleven healthy participants without brain injury, each of which was recruited from Uegahara Hospital, formed the healthy control group.

To be included in the study, the participants met these 10 criteria: (1) were native Japanese with ≥12 yr of education, (2) had no degenerative disorder, (3) had no neurological or psychiatric disorders before their brain damage, (4) were ≥0.25 yr post-onset of their disorder, (5) had no ocular palsy, (6) had sufficient motor ability to perform the trial tasks and not be limited by upper-limb palsy or apraxia, (7) were able to perform activities related to daily life including feeding themselves and routine use of the toilet, (8) were able to understand and follow task instructions, (9) had routinely used an electronic device with a flat touch interface (e.g., a smartphone, a cash dispenser, and a ticket vending machine) before onset of brain damage, and (10) were able to recognize Arabic numerals.

Demographic features and basic neuropsychological assessments

The demographic features investigated were age, gender, level of education, and time in years post-onset. General cognitive function was evaluated using the Japanese version of the Mini-Mental State Examination (MMSE-J; Sugishita, & Hemmi, 2010). Verbal intelligence quotient (VIQ) and performance intelligence quotient (PIQ) were evaluated using the Japanese version of the Wechsler Adult Intelligence Scale (WAIS-J; Fujita, 2006). Visuospatial function was evaluated using the Japanese versions of the Trail Making Test A and B (TMT-A and -B; Kashima, Handa, & Katoh, 1986), which were originally designed to evaluate visual attention (TMT-A) and switching ability (TMT-B). The time limit for each section was 600 sec. If the participant had not completed a section during this time, the trial was terminated, and a value of 600 sec was used for statistical analysis. Visuospatial working memory capacity was evaluated using the forward and backward tapping span from the Clinical Assessment for Attention (CAT; Kato, 2006), in which participants encode and recall the order of presentation of spatial locations marked in sequence. The printed black square arrangement of the tapping span imitates the sequence of the Corsi Block-Tapping Task (Milner, 1971). Phonological working memory along with visuospatial working memory was evaluated using the forward and backward digit span from the CAT. These neuropsychological tests have been demonstrated to have content validity and reliability (MMSE-J, Sugishita, & Hemmi, 2010; WAIS-J, Fujita, 2006; TMT-A and -B, Kodama, & Asada, 2008; CAT, Kato, 2006).

Individuals in the Bálint syndrome group, the USN group, and the memory deficits control group completed the MMSE-J, the WAIS-J, the TMT-A and -B, the forward and backward tapping span, the forward and backward digit span from standardized neuropsychological tests. Among the healthy control group, individuals completed only the Japanese version of the MMSE-J.

Numeric input task using electronic devices

Electronic devices assign functions to specific buttons; therefore, the ability to use electronic devices was tested using three button-pressing tasks, with Arabic numerals assigned to the buttons. Unlike Indo-European languages, the Japanese language uses three different writing systems, each of which has at least 46 characters. Therefore, compared with those systems, Arabic numerals, which are also commonly used in Japan, are easier to use in this type of experiment.

We developed application software for a tablet-type device to judge the difficulty of operating electronic devices. Our goal was to evaluate the participants' performance using a numeric interface that had real-life applicability. Therefore, the interface layouts of the application reproduced the screen of inputting a digit sequence into a cash dispenser in Japan. In the case of Japanese cash dispenser, the numeric input of PIN (personal identification number) is carried out on a flat touch interface, and a button array of number changes because of prevention of crimes. There was an array that consisted of four light gray buttons (each measuring 20 × 20 mm) aligned vertically by three light gray buttons aligned horizontally, except for a missing button at the bottom left position. The array was presented on a white background. There were also black digits (0–9) in the center of each button, except for the bottom right button, which represented a function to return to the previous input. This button array consisted of two patterns, a normal pattern made up of the digits 0–9 (e.g., the top left was 1, the top right was 3, and the bottom center was 0) for each task and a random pattern in which the sequence of digits was randomized across the buttons for each task (Fig. 1).

When a button was inputted by a participant, a solid black circle was displayed horizontally in the upper part of the screen as visual feedback. However, there was no kinesthesia (e.g., vibration) or auditory (e.g., buzzer) feedback. The reaction time was measured and recorded from the first input to the last input by the tablet-type device.

Participants were instructed to input a digit sequence of four, seven, and 11 digits (e.g., 3578, 9512357, 15987532159) into a tablet-type device with a flat touch interface (Xperia Z2; device size, 266 × 172 × 6.4 mm; Sony Corporation, Tokyo). Each digit sequence was displayed on a laptop screen (Sony VAIO VPCS14AFJ; 329 × 228.5 × 31.5 mm; Sony Corporation) in 60-point MS Gothic font in black ink on a white background using PowerPoint 2010 (Microsoft Corporation, Redmond, WA) and was viewed by the subjects from a distance of 50 cm. The tablet-type device was placed on the keyboard of the laptop across a sheet of rigid plastic. This sheet of plastic was used to prevent activation of the laptop keyboard. The indicated digit sequence remained until the participant finished entering the digits into the device.

We used three experimental designs for these investigations: (1) In the button array on the interface of the tablet-type device, two patterns were tested: one that used the normal sequential pattern and a second that used a random pattern (as described above; Fig. 1). A random pattern of numbers on a button array is used for inputting a PIN at cash dispensers in Japan. (2) To compare finger trajectories as the digits were inputted, two sequence patterns were tested: one that displayed a digit sequence based on inputting the neighboring button (short-trajectory pattern) and a second that had a random digit sequence (long-trajectory pattern) (Fig. 2). In setting up the application software, all digit sequence using each trials were displayed on the tablet-type device at the same time before the start of the trial because the inputting location is decided. We generated a task based on the digit sequence displayed on the interface of the tablet-type device. On setting, the short-trajectory pattern and the long-trajectory pattern that each participant carried out were the same distance. (3) In consideration of the left-sided spatial neglect among some of the participants, two patterns were tested with the four-digit sequences: one that started from the right side of the button array and a second that started from the left side of the array.

Figure 3 shows the procedure of the trials. Trials 1–8 used the normal button array and trials 9–16 used the random pattern of numbers in the button array on the interface of the tablet-type device. A new random pattern for the numbers was generated for each trial during trials 9–16. After the first eight trials were completed, there was a 1-min break and explanation about the random pattern of the button array in the next eight trials, which would be used in combination with the same digit sequences as for the normal button array for each participant. Trials 1, 2, 5, 7, 9, 10, 13, and 15 were set up as short-trajectory sequences, and trials 3, 4, 6, 8, 11, 12, 14, and 16 were set up as long-trajectory sequences. Each participant entered 16 sequences in total. We confirmed the accomplishment level of each participant by the degree of difficulty. In addition, to avoid a negative influence on an individual's motivation, early trials were easier to allow for likely completion. Therefore, the order of the trials was based on their degree of difficulty rather than being randomly assigned.

We recorded the performance of each participant with a digital video camera (Sony Handycam CX630V; Sony Corporation) and conducted quantitative analyses of the hesitations that occurred while they inputted the numbers into the device. The definition of a hesitation was a pause in the inputting of the numbers of >3 s. We characterized the hesitations into five subcategories and three main categories, which allowed us to quantitatively compare these hesitations (for subcategory and category details, see “A comparison of hesitation types during the inputting of digit sequences among the four groups” in the Results).

We established the following time limits on each trial because the participants who could not accomplish the task required a substantial amount of time: (1) The time limit for each digit sequence was 60 s. (2) No more than four errors were allowed for each digit sequence.

Statistical analysis

Two analyses were performed: (1) a comparison of the performance of the Bálint syndrome group (n = 7), the USN group (n = 7), the memory deficits control group (n = 7), and the healthy control group (n = 11) and (2) a comparison of performances of mild Bálint syndrome group (n = 5), the USN group (n = 7), the memory deficits control group (n = 7), and the healthy control group (n = 11).

Age, education, and MMSE-J score had unequal variances and were compared across the four groups using the Kruskal-Wallis test. Other neuropsychological data (VIQ, PIQ, TMT-A and -B scores, and digit span and tapping span scores) and the number of years post-onset were nonparametric and were compared across the Bálint syndrome group, the USN group, and the memory deficits control group using the Kruskal-Wallis test. Post hoc pairwise comparisons were made using the Steel-Dwass test.

For each digit sequence, the time taken to input the digit sequence and the number of times that hesitations occurred were each compared across the four groups using the Kruskal-Wallis test. Post hoc pairwise comparisons were made using the Steel-Dwass test.

For each group, we analyzed the following three comparisons with respect to the time taken to input the digit sequence using the Mann-Whitney U-test: (1) the short-trajectory pattern versus the long-trajectory pattern for each sequence length, (2) the normal button array versus the random pattern array for each sequence length, and (3) the trials starting from the right side versus the trials starting from the left side of the button array for the four-digit sequence length only.

If the participant had not inputted all the numbers in the digit sequence within the time limit of 60 s or within the limit of four errors, the trial was terminated, and values of 30 s for four-digit sequences, 36 s for seven-digit sequences, and 55 s for 11-digit sequences were used for the statistical analyses. These values were determined according to the longest time period among the participants who were able to accomplish these tasks.

Regarding the quantitative analyses, the hesitations classified into larger categories were analyzed as follows: (1) The absolute number of hesitations was calculated, as was the percentage of each hesitation category relative to all hesitation types. (2) For each group, the hesitation frequencies were compared across the four groups of participants using Fisher's exact test.

Excel 2010 (Microsoft Corporation) with add-in Statcel 4 software (The Publisher OMS Ltd., Tokyo) was used for all statistical analyses. Significance was set at $p < 0.05$. All tests were two-tailed.

RESULTS

Demographic features and neuropsychological data

Table 1 shows the demographic characteristics (age, gender, education level, and years post-onset) and neuropsychological test scores for each of the seven participants with Bálint syndrome and

USN and the average for each control group. The Bálint syndrome group and the USN group and the two control groups did not differ with respect to age (Kruskal-Wallis test, $p = 0.19$) or education (Kruskal-Wallis test, $p = 0.09$). MMSE-J scores differed across the Bálint syndrome group, the USN group, the memory deficits control group, and the healthy control group (Kruskal-Wallis test, $p < 0.01$). Post hoc analysis of the scores showed that the Bálint syndrome group, the USN group, and the memory deficits control group had lower scores than the healthy control group (Steel-Dwass test, all $p < 0.05$).

Regarding the comparison of the Bálint syndrome group, the USN group, and the memory deficits control group, VIQ (Kruskal-Wallis test, $p = 0.91$) and TMT-A (Kruskal-Wallis test, $p = 0.14$) scores and the digit span forward (Kruskal-Wallis test, $p = 0.32$), digit span backward (Kruskal-Wallis test, $p = 0.35$), and years post-onset (Kruskal-Wallis test, $p = 0.29$) data were similar for the Bálint syndrome group, the USN group, and the memory deficits control group.

Conversely, the scores on the four tests that involved visuospatial function differed across the Bálint syndrome group, the USN group, and the memory deficits control group (Kruskal-Wallis test: PIQ, $p < 0.01$; TMT-B, $p = 0.01$; tapping span forward, $p < 0.01$; and tapping span backward, $p < 0.01$). Post hoc comparisons showed that PIQ and TMT-B and tapping span forward and backward were lower for the Bálint syndrome group and the USN group than for the memory deficits control group (Steel-Dwass test, all $p < 0.05$). Furthermore, the tapping span backward was lower for the Bálint syndrome group than for the USN group (Steel-Dwass test, $p < 0.05$).

When the 2 participants with severe Bálint syndrome were excluded, the remaining 5 participants with mild Bálint syndrome, the USN group, and the two control groups still had similar distributions of age (Kruskal-Wallis test, $p = 0.43$), education (Kruskal-Wallis test, $p = 0.27$), and the mild Bálint syndrome group, the USN group, and the memory deficits control group had similar VIQ (Kruskal-Wallis test, $p = 0.92$) and TMT-A (Kruskal-Wallis test, $p = 0.31$) scores and the digit span forward (Kruskal-Wallis test, $p = 0.29$), digit span backward (Kruskal-Wallis test, $p = 0.77$), and years post-onset (Kruskal-Wallis test, $p = 0.43$). MMSE-J scores differed across the mild Bálint syndrome group, the USN group, the memory deficits control group, and the healthy control group (Kruskal-Wallis test, $p < 0.01$). Post hoc analysis of the scores showed that the mild Bálint syndrome group, the USN group, and the memory deficits control group had lower scores than the healthy control group (Steel-Dwass test, all $p < 0.05$). The scores of PIQ and TMT-B and tapping span forward and backward differed across the mild Bálint syndrome group, the USN group, and the memory deficits control group (Kruskal-Wallis test: PIQ, $p < 0.01$; TMT-B, $p < 0.05$; tapping span forward, $p < 0.05$; and tapping span backward, $p < 0.01$). Post hoc comparisons showed that PIQ and tapping span forward and backward were lower for the mild Bálint syndrome group and the USN group than for the memory deficits control group (Steel-Dwass test, all $p < 0.05$). Regarding TMT-B, the USN group had lower score than the memory deficits control group (Steel-Dwass test, $p < 0.05$).

Comparisons of time and hesitations during the numeric input tasks across the five groups

Figure 4 shows the mean time taken and the number of times that hesitations occurred during the inputting of each digit sequence for all four experimental groups. The time taken and the number of hesitations differed across the Bálint syndrome group, the USN group, the memory deficits control group, and the healthy control group for digit sequences of all lengths (Kruskal-Wallis test, all $p < 0.01$).

A post hoc analysis of the time taken showed that the Bálint syndrome group took longer than the USN group, the memory deficits control group, and the healthy control group for digit sequences of all lengths (Steel-Dwass test, all $p < 0.01$). In addition, the USN group took longer than the healthy control group for digit sequences of all lengths (Steel-Dwass test, all $p < 0.01$) and the memory deficits control group for sequences of 11 digits (Steel-Dwass test, $p < 0.01$), but the USN group and the memory deficits control group took a similar amount of time for sequences of four digits and seven digits (Steel-Dwass test, all $p > 0.05$). The memory deficits control group also took longer than the healthy control group (Steel-Dwass test, all $p < 0.01$) for digit sequences of all lengths.

A post hoc comparison of the hesitations showed that the Bálint syndrome group had more hesitations than the USN group (Steel-Dwass test, all $p < 0.01$), the memory deficits control group (Steel-Dwass test, all $p < 0.01$), and the healthy control group (Steel-Dwass test, all $p < 0.01$) for digit sequences of all lengths. In addition, the USN group had more hesitations than the healthy control group (Steel-Dwass test, all $p < 0.01$) for digit sequences of all lengths and the memory deficits control group for sequences of seven digits and 11 digits (Steel-Dwass test, all $p < 0.01$), but the USN group and the memory deficits control group had a similar number of hesitations for sequences of four digits (Steel-Dwass test, $p > 0.10$). Furthermore, the memory deficits control group had more hesitations than the healthy control group for sequences of four digits and 11 digits (Steel-Dwass test, all $p < 0.05$), but the memory deficits control group and the healthy control group had a similar number of hesitations for sequences of seven digits (Steel-Dwass test, $p > 0.10$).

When the participants with severe Bálint syndrome who could not accomplish the tasks in every digit sequence were excluded, the mild Bálint syndrome group took a longer period of time and had more hesitations than the USN group, and the two control groups. The time taken and the number of hesitations differed across the mild Bálint syndrome group, the USN group, the memory deficits control group, and the healthy control group for digit sequences of all lengths (Kruskal-Wallis test, all $p < 0.01$). A post hoc comparison of showed that the mild Bálint syndrome group took longer than the USN group, the memory deficits control group, and the healthy control group for digit sequences of all lengths (Steel-Dwass test, all $p < 0.01$) and had more hesitations than the USN group, the memory deficits control group, and the healthy control group for digit sequences of all lengths (Steel-Dwass test, all $p < 0.01$).

The effect of the button array type on the numeric input tasks among the five groups

Figure 5 shows the mean time for inputting digit sequences with a normal and random button array pattern on the interface of the tablet-type device for all five experimental groups. For digit sequences of all lengths, the random pattern of the button array took longer than did the normal pattern of the button array for the USN group (Mann-Whitney U-test, $p < 0.01$ for sequences of four digits, $p < 0.05$ for sequences of seven digits, $p < 0.01$ for sequences of 11 digits), the memory deficits control group (Mann-Whitney U-test, $p < 0.05$ for sequences of four digits, $p < 0.01$ for sequences of seven digits, $p < 0.01$ for sequences of 11 digits), and the healthy control group (Mann-Whitney U-test, all $p < 0.01$). Conversely, for digit sequences of all lengths, the two patterns of the button array took a similar amount of time for the Bálint syndrome group (Mann-Whitney U-test, $p > 0.05$ for sequences of four digits, $p > 0.05$ for sequences of seven digits, $p > 0.10$ for sequences of 11 digits). Regarding the mild Bálint syndrome group, the result was similar only when inputting of 11-digit sequences (Mann-Whitney U-test, $p > 0.05$).

The effect of trajectory length on the numeric input tasks among the five groups

For digit sequences of all lengths, the time taken to input a digit sequence did not differ with respect to which pattern of digit sequences was tested, that is, the short trajectory pattern versus the long trajectory pattern (Mann-Whitney U-test, $p > 0.60$ for the Bálint syndrome group, $p > 0.60$ for mild Bálint syndrome group, $p > 0.80$ for the USN group, $p > 0.40$ for the memory deficits control group, and $p > 0.80$ for the healthy control group).

The effect of left-sided hemineglect on the numeric input tasks among the five groups

The time taken to input a four-digit sequence did not differ with respect to which trial of digit sequences was tested, that is, the trials that began with a digit on the right side of the array versus those that began with a digit on the left side (Mann-Whitney U-test, $p > 0.60$ for the Bálint syndrome group, $p > 0.60$ for the mild Bálint syndrome group, $p > 0.80$ for the USN group, $p > 0.80$ for the memory deficits control group, $p > 0.60$ for the healthy control group).

A comparison of hesitation types during the numeric input tasks among the five groups

We classified the hesitations according to the following five subcategories: (1) A participant's finger did not move before pushing the button. (2) A participant's finger stopped while pointing toward the laptop screen (on which the digit sequence is displayed). (3) A participant's finger wavered in the air before pushing a button. (4) A participant hesitated once and pushed the same button again. (5) A participant's finger stopped while the participant spoke to the author who was running the experiment. In this study, we were not able to examine the gaze of the participant. However, we determined that a finger that did not move reflected the gaze of the participant toward the digit sequence on the laptop screen based on our observations during the experiments. In contrast, a wavering finger reflected the exploration of the button array on the tablet-type device. Therefore, the five subcategories were then sorted into the following three main categories, (a) hesitations related to gazing toward the digit sequence on the laptop screen, (b) hesitations related to exploration of the button array on the tablet-type device, and (c) hesitations for other reasons. Specifically, subcategories (1) and (2) became category (a), subcategory (3) became category (b), and subcategories (4) and (5) became category (c).

Figure 6 shows the percentage of each of the three main categories for the Bálint syndrome group, the mild Bálint syndrome group, the USN group, and the memory deficits control group. For the healthy control group, hesitation for gazing occurred only once during the digit inputting task because those individuals carried out the inputting operations more effectively than individuals from the Bálint syndrome, the USN group, and the memory deficits control group. Therefore, the healthy control group was not included in the comparison of hesitation types. For the USN group and the memory deficits control group, the percentage of hesitations related to gazing (62 hesitations or 62.0% for the USN group and nine hesitations or 60.0% for the memory deficits control group) was higher than the percentage of hesitations for exploration (34 hesitations or 34.0% for the USN group and five hesitations or 33.3% for the memory deficits control group). For the Bálint syndrome group, however, the percentage of hesitations for exploration (231 hesitations or 74.3%) was higher than the percentage of hesitations for gazing (79 hesitations or 25.4%). A comparative analysis showed that the percentage of hesitations for exploration for the Bálint syndrome group was significantly higher as compared with that of the USN group and the memory deficits control group (Fisher's exact test, $p < 0.05$). The results were similar when the participants with sever Bálint syndrome were excluded. For the mild Bálint syndrome group, the percentage of hesitations for exploration (134 hesitations or 75.3%) was higher than the percentage of hesitations for gazing (44 hesitations or 24.7%). A comparative analysis showed that the percentage of hesitations for exploration for the mild Bálint syndrome group was significantly higher as compared with that of the USN group and the memory deficits control group (Fisher's exact test, $p < 0.05$).

DISCUSSION

This is the first report that compared the Bálint syndrome group with the USN group with respect to the ability to operate modern electronic devices. Our study yielded three findings. First, our findings confirm previous results that participants with Bálint syndrome take longer to input a digit sequence into an electronic device (Sunagawa et al., 2015). Importantly in this study, participants with Bálint syndrome took a longer period of time and had more hesitations than individuals in the USN group. Second, only participants with Bálint syndrome showed no difference with respect to their mean completion time for a random pattern versus a normal pattern on the button array. In the other groups, the random pattern took longer than the normal pattern. In other words, participants with Bálint syndrome needed as much time on the normal pattern array as on the random pattern array. Third, participants with Bálint syndrome had a high percentage of hesitations for exploration of the button array on the tablet-type device. These were not simply the results of moving distance of the finger because there was no difference between the results by the short trajectory pattern and the long trajectory pattern. Additionally, these results also were not only the factor of left-sided neglect because the poor performance remained when a digit sequence did not depend on the left side of the display. The aforementioned results were similar to the results after excluding participants with severe Bálint syndrome. To sum up the results of the Bálint syndrome participants, even if the symptoms were mild, the longer time required for the numeric input operation is likely to have resulted from the need to explore the array to find each sequential digit. The random pattern and the normal pattern on the button array resulted in similar times, because the participants with Bálint syndrome could not grasp the placement of the button array and always had to explore for numbers.

Among the participants with Bálint syndrome in this study, dorsal simultanagnosia was present in each of the participants. Additionally, they had a lower score for tapping span as measured by an assessment similar to the Corsi Block-Tapping Task, which evaluates visuospatial working memory (Corsi, 1972; Kessels et al., 2000; Parmentier, 2011), than participants in the USN and memory deficits control groups. In fact, participants with the dorsal simultanagnosia of Bálint syndrome took longer for numeric input operations because they judged the numbers as information rather than considering the positional relationship of the button array. Therefore, the time they required when working with the normal pattern on the button array was similar to that with the random pattern, and they experienced more hesitations for exploration of the button array. This inability is likely to be associated with impaired remapping of the positional relationships of the digits for each button because of visuospatial working memory deficits. In addition, participants with Bálint syndrome had a lower score for tapping span and a poor performance for the numeric input tasks relative to the USN group. With respect to visual search tasks and the ability to remember locations, visuospatial working memory is severely impaired in Bálint syndrome patients as compared with subjects with right-parietal damage including left-sided USN (Funayama, Nakagawa, & Sunagawa, 2015). This previous study and our results advance our understanding of the need for visuospatial working memory in numeric input operations on electronic devices.

It was consistent that participants with USN also took longer than participants with memory deficits to carry out numeric input operations. Based on an analysis of the hesitations, there was a high percentage of hesitations for gazing among participants from both groups. In the case of individuals with USN, this was not caused by neglect on the left side. Instead, the results from both groups were likely to be caused by forgetting the location of the numbers to be inputted in the digit sequence during the numeric input operation. Several studies have investigated visuospatial working memory among individuals with USN. Patients who exhibit or have exhibited neglect show a remapping deficit or visuospatial working memory deficit (Pisella, 2017). For some neglect patients, visuospatial working memory deficits are specifically impaired with respect to detecting location changes (Pisella, Berberovic, Mattingley, 2004; Malhotra et al., 2005). The performance of the neglect patients was significantly impaired relative to controls for the long-trajectory sequence, consistent with a spatial working memory deficit (Malhotra et al., 2005). These previous studies support the possibility that visuospatial working memory deficits among participants with USN also influence the time needed for numeric input operations.

Regarding interfaces of modern electronic devices, visuospatial working memory deficits could be improved if a small amount of visual information was presented within a narrow field of view because individuals with visuospatial working memory deficits were unable to grasp the entire interface layout in these experiments. In addition, Rizzo, & Vecera (2002) reported that ventral pathways involved in the perceptions for colors, objects, and faces. Therefore, it may be necessary to design such interfaces with respect to a color and the form to promote activation of ventral pathway that is not affected rather than dorsal pathway. Furthermore, the spread of electronic devices that do not require numeric inputs such as biometric authentication systems (e.g., fingerprint authentication, iris authentication) is expected to help individuals with visuospatial working memory deficits.

The participants with memory deficits in this study had lower scores for the MMSE-J than individuals from the healthy control group. Additionally, TMT-A and -B scores among the participants with memory deficits were also lower than the average of 50 s for a person with a normal (table 1) (Toyokura, Tanaka, Furukawa, Yamanouchi, & Murakami, 1996). Therefore, it is assumed that general cognitive function, visual attention, and switching ability influence the numeric input operations on electronic devices because participants with memory deficits had poor performances relative to healthy controls. Furthermore, participants with ABI had a lower score for tapping span and a poor performance for the numeric input tasks relative to the USN group. In contrast, the fact that participants with memory deficits had higher scores for the numeric input tasks than the Bálint syndrome group and the USN group is consistent because the individuals did not need to memorize each digit sequence.

Limitations of the study

Our study has several limitations that should be considered when interpreting the results. First, the number of participants with Bálint syndrome or with USN was small. However, Bálint syndrome is rarely found in patients with brain damage, which precludes studying a large cohort, and participants were excluded if they could not perform activities related to daily living. Second, the input data were limited to Arabic numerals, which do not represent all Japanese language characters necessary for the operation of modern electronic devices. However, we tried to design the button-pressing tasks to be as simple as possible and believe that use of a Japanese writing system would have been more difficult for participants with a visuospatial deficit. Finally, we did not examine eye gaze trajectory (e.g., with the use of Eyetracker™, Cambridge Research Systems, Rochester, UK) to investigate exploration of the button array. Pisella et al. (2015) demonstrated that the visuospatial working memory of patients with PCA decreases based on the analysis of eye gaze trajectory using Eyetracker. This deficit is therefore only expressed as search time increases, which reflects an increase in the number of saccades necessary to scan the entire visual display with a smaller attentional field (Pisella et al., 2015). However, we did consider visuospatial working memory deficits with our qualitative analysis of the hesitation of each individual's finger. To analyze in detail, the effect of visuospatial working memory on the operation of modern electronic devices, it may be necessary to investigate eye gaze trajectory.

Conclusion

Based on the results of this study, individuals with a dorsal simultanagnosia are likely to face difficulties when using modern electronic devices. In particular, factors related to visuospatial working memory should be considered as possible problems. The number of people with cognitive deficits, including visuospatial working memory impairment, are necessary to use the electronic devices in modern society. Regarding the modern electronic devices, we should consider visuospatial working memory to facilitate the use of more people.

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Disclosure statement

The authors report no conflict of interest.

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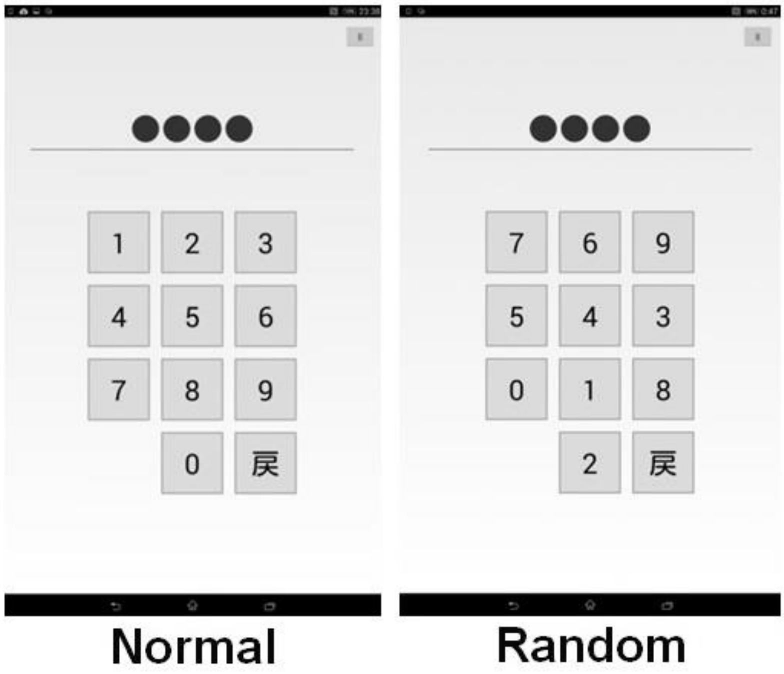

Figure 1. Screen images of the setups for the button array trials.

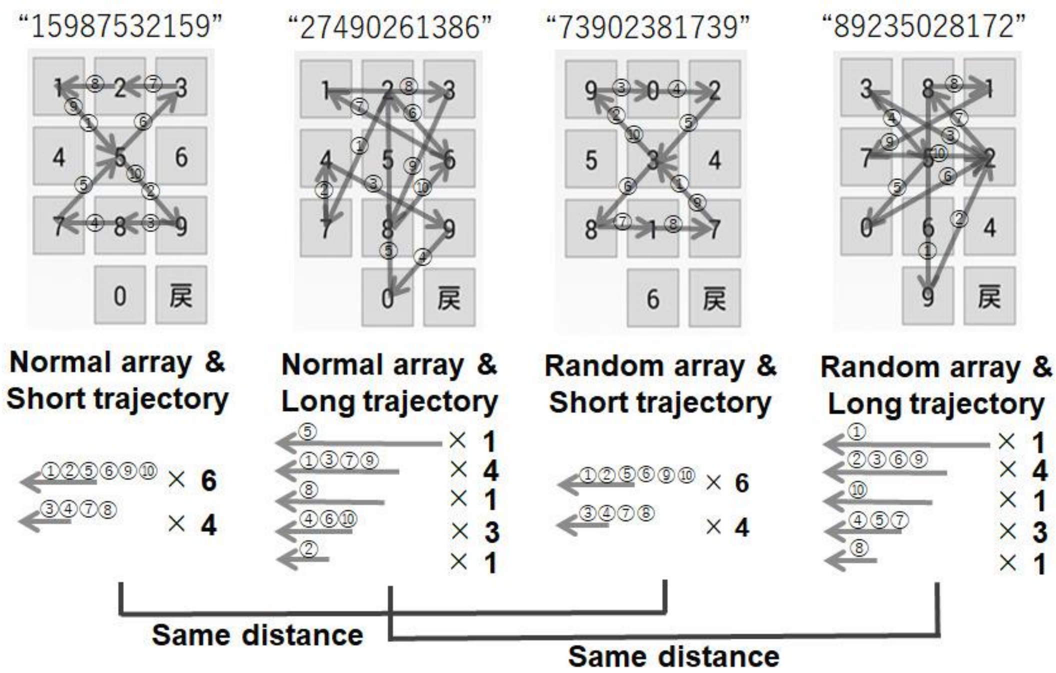

Figure 2. A comparison of short and long trajectories.

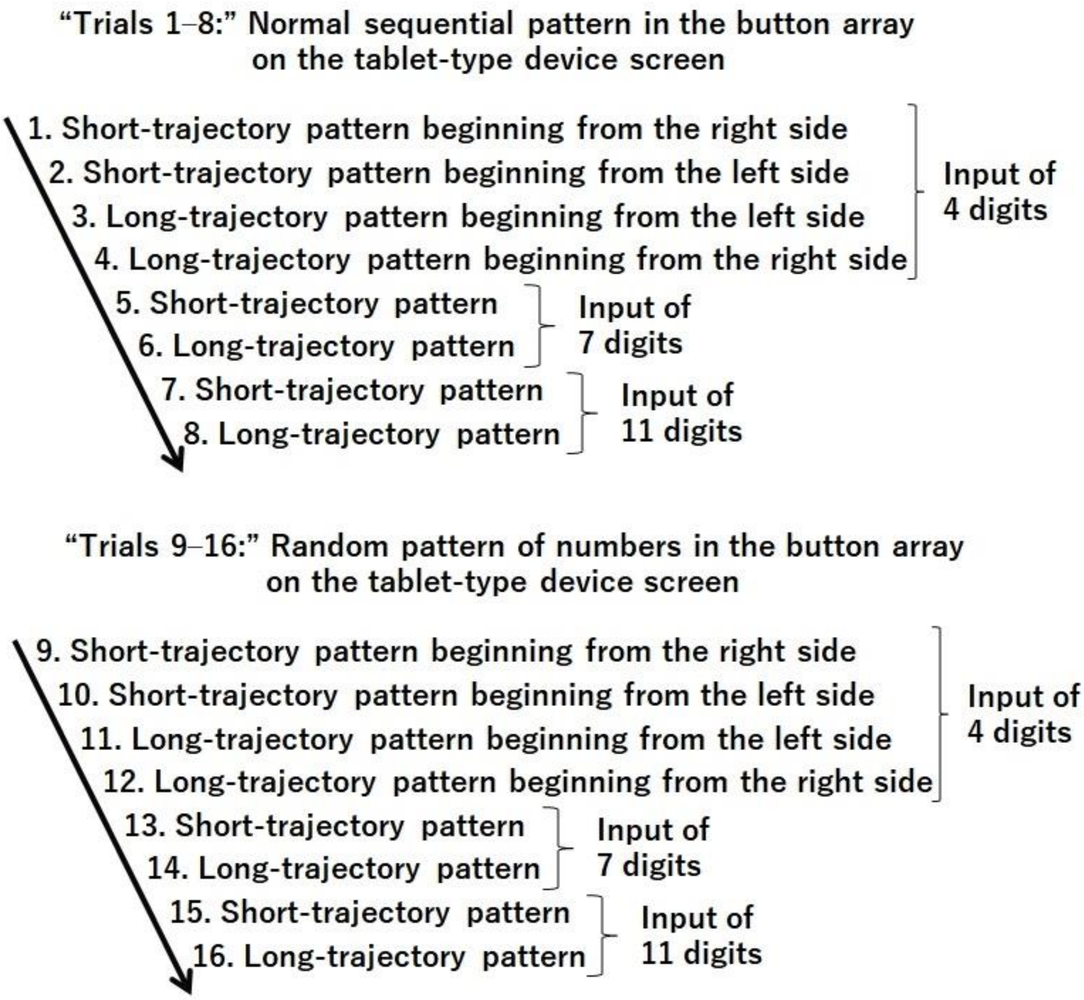

Figure 3. The procedure of the trials.

Table 1. Demographic Characteristics and Neuropsychological Data.

Participant or Group	Gender	Age, yr	Education, yr	Yr Since Onset	MMSE-J Score[a]	VIQ[b]	PIQ[b]	TMT-A Time,[c] s	TMT-B Time,[d] s	digit span forward [e]	digit span backward [f]	tapping span forward [g]	tapping span backward [h]
Participant with Bálint syndrome													
1	F	65	12	5	14	64	45	600 (DNF)	600 (DNF)	5	DNF	2	DNF
2	F	70	12	0.5	20	67	50	600 (DNF)	600 (DNF)	6	3	4	DNF
3	M	59	12	9	28	108	55	269	280	7	DNF	2	DNF
4	M	52	12	5	25	63	62	156	600 (DNF)	4	3	4	2
5	M	64	12	1	24	94	54	177	600 (DNF)	4	5	4	2
6	M	58	16	4	20	59	48	600 (DNF)	600 (DNF)	5	3	2	DNF
7	M	63	12	0.3	29	100	67	120	174	5	5	5	4
Participant with USN													
1	M	52	16	10	27	60	58	260	404	6	5	5	4
2	M	71	12	11	20	89	62	120	362	5	4	4	3
3	M	43	12	1	25	65	53	72	462	6	4	5	4
4	M	72	16	10	28	93	59	221	333	5	4	5	4
5	M	67	15	1	23	113	56	507	600 (DNF)	6	4	2	3
6	M	46	13	6	29	97	60	175	224	6	4	4	3
7	M	32	12	0.3	20	77	59	639	870	6	2	2	3
Group													
Memory Deficits control (n = 7)	5M, 2F	49.5 ± 12.9	14.8 ± 1.5	9.4 ± 9.7	26.5 ± 2.6	81.4 ± 22.8	88.2 ± 20.8	151.0 ± 62.1	212.2 ± 138.9	5.7 ± 1.1	4.1 ± 1.2	5.4 ± 0.5	4.2 ± 0.4
Healthy control (n = 11)	6M, 5F	54.2 ± 6.7	14.0 ± 2.2	—	29.6 ± 0.8	NA	NA	NA	NA	NA	NA	NA	NA

Note: Group data are shown as the number of individuals (for gender) or as the mean ± SD. Maximum time on the TMT-A and TMT-B is 600 s; participants who did not finishing within that time limit are indicated by DNF (did not finish). F, female; M, male; MMSE-J, Japanese version of the Mini-Mental State Examination; NA, not assessed; VIQ, verbal intelligence quotient; PIQ, performance intelligence quotient; TMT-A, Trail Making Test A; TMT-B, Trail Making Test B.

[a]Cutoff, 23. [b]Normal range, 70–130. [c]Average for 50 s, 109.2. [d]Average for 50 s, 150.2. [e]Average for 50 s, 6.4. [f]Average for 50 s, 4.4. [g]Average for 50 s, 5.8. [h]Average for 50 s, 4.9.

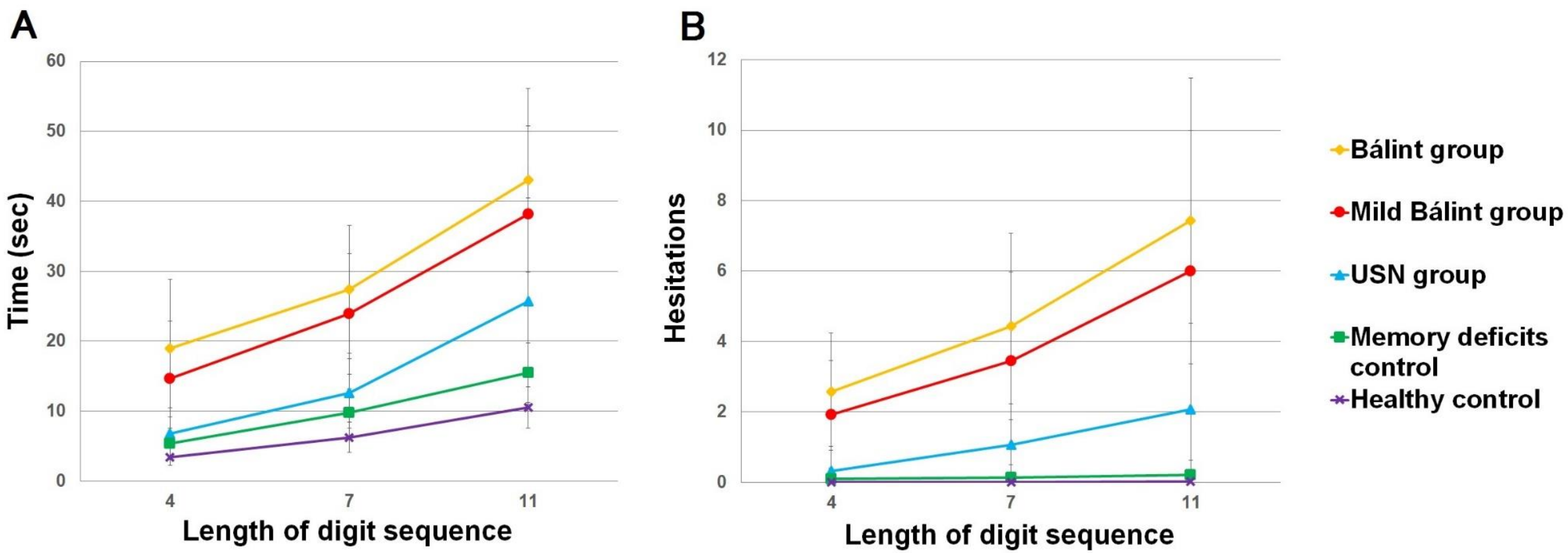

Figure 4. Comparisons of (A) time for completion and (B) the number of hesitations during the numeric input tasks across the five participant groups, individuals with Bálint or with mild Bálint or with USN and memory deficit and healthy controls.

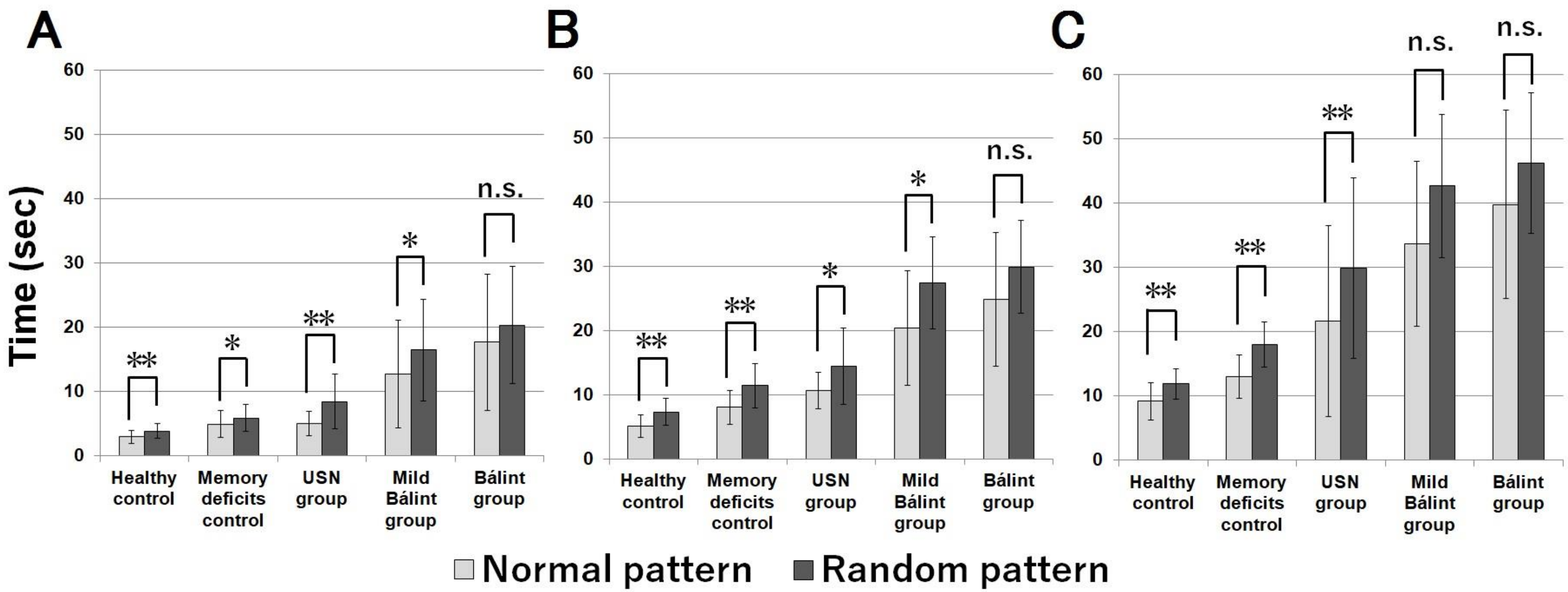

Figure 4. Comparisons of (A) time for completion and (B) the number of hesitations during the numeric input tasks across the five participant groups, individuals with Bálint or with Mild Bálint or with USN and memory deficit and healthy controls.

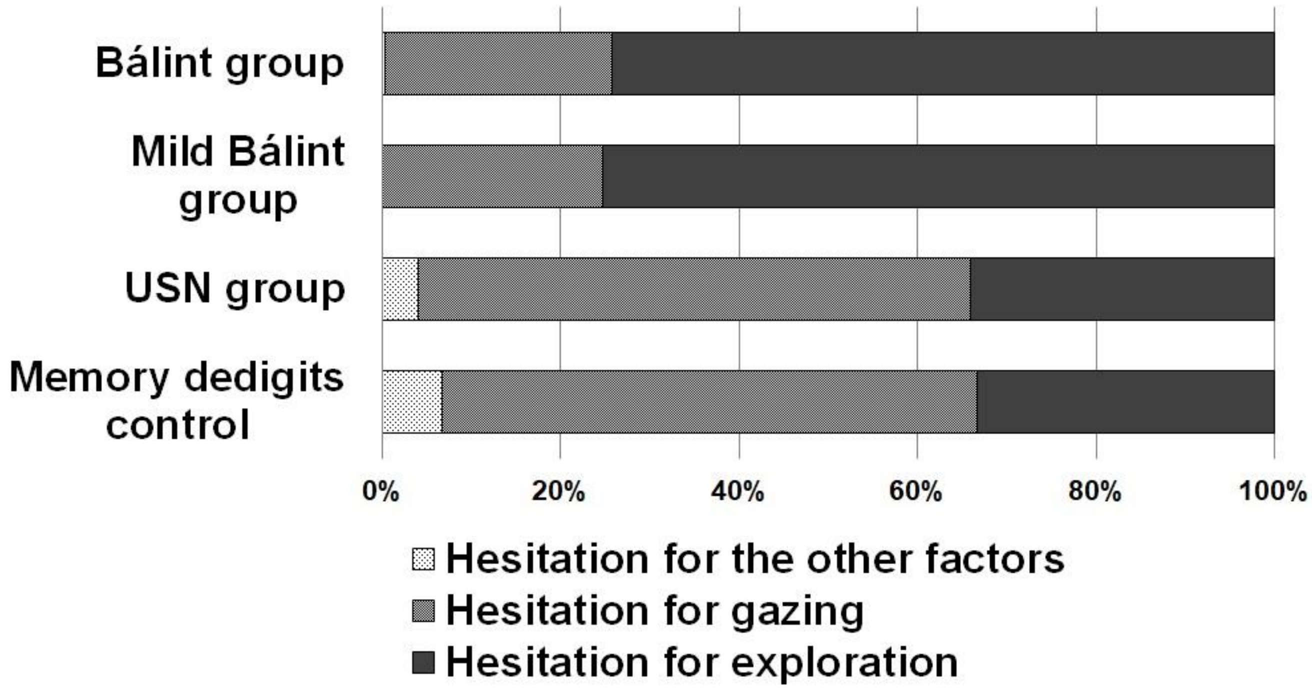

Figure 6. Comparison of hesitation types among Bálint group, mild Bálint group, USN group, and memory deficits control.