Assessment of convalescent brain-damaged patients using a virtual shopping test with different task difficulties

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ABSTRACT

We developed a Virtual Shopping Test for realistic cognitive assessment using virtual reality technology. The objective of this study was to investigate differences in task performance, brain activation, and subjective assessments in relation to the task difficulty level. Subjects were asked to buy two specific items in Task 1, four items in Task 2, and six items in Task 3 at a virtual mall. The tasks and questionnaires were conducted by convalescent brain-damaged patients and healthy adults. Hemodynamic changes in the prefrontal cortex (PFC) during activation due to the tasks were examined using functional near-infrared spectroscopy. The mean total time was longer for the patients than for the healthy subjects in all tasks. PFC responses in the patients were greater in Task 2 than in Task 1. The patients subjectively evaluated these tasks as more difficult than healthy adults. Although task performance as well as PFC responses were not significantly changed in the healthy adults, they could subjectively evaluate differences between the three task levels, whereas the patients could not, which indicated that patients could not clearly distinguish between differences in the difficulty of the tasks performed. Taken together, the results suggest that the difficulty of the 4-item shopping task may have been sufficient to cause brain activation in the brain-damaged patients.

1. INTRODUCTION

As one of the most serious problems in an unprecedented aged society, the percentage of elderly people with various physical and mental diseases is increasing. Higher brain dysfunctions due to brain damage and aging lead to many difficulties in daily life. However, it is reported that results of conventional neuropsychological tests sometimes disagree with the cognitive function level in real life of the patients (Chaytor et al, 2006; Ord et al, 2010). Therefore, an environment that is similar to everyday life conditions is important for evaluating and training cognitive functions. As a consequence, a focus has recently been placed on virtual reality (VR) techniques.

In cognitive rehabilitation, exercises with an appropriate difficulty level for each individual may increase the patient's motivation and produce good results. However, difficulties have been associated with establishing an appropriate task level because of the lack of evidence on its effectiveness (Cicerone et al, 2011). Although various VR techniques have been proposed for cognitive rehabilitation (Zhang et al, 2003; Knight et al, 2006; Kang et al, 2008), a small number of study including a virtual action planning supermarket considered the task difficulty level and/or related brain activation (Josman et al, 2009; Tarnanas et al, 2012).

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We previously developed a Virtual Shopping Test (VST) for a realistic assessment of cognitive function using VR technology (Okahashi et al, 2013). In the present study, the VST was modified to a revised version (VST-R) that had three different task difficulty levels. Subjects were asked to buy specific 2 items, 4 items, and 6 items in a different virtual mall in each task. The system could also output event signals that were synchronized with the user's PC operation. We used these signals to assess event-related brain activation.

The objective of this study was to investigate the differences on task performance, brain activation and subjective assessment in relation to the task difficulty level. VST-R was conducted and questionnaires were answered by convalescent brain-damaged patients and healthy young adults. Hemodynamic changes in the prefrontal cortex (PFC) during activation due to the tasks were examined using functional near-infrared spectroscopy (fNIRS): a non-invasive technique. A previous study reported that executive function and attention were related to activation of the PFC (Godefroy, 2003). We hypothesized that each task level would activate the brain differently and lead to more subjective assessments. In addition, differences were expected in the activation pattern between the two groups.

2. METHODS

2.1 The Virtual Shopping Test-Revised (VST-R)

The hardware system included a personal computer, touch screen (LCD-MF222FBR-T, I-O DATA), and 16-channel OEG-16 fNIRS system (Spectratech Co., Yokohama, Japan). Figure 1 shows the experimental system with VST-R screen and fNIRS channel arrangement on the forehead. A visual environment consisted of a Japanese shopping mall was developed with Metasequoia and Open GL. The width of the virtual mall was about five meters and the depth was about one hundred meters. An audio environment of natural sounds associated with a shopping mall was also provided. By touching the bottom of the screen, users could move forward and turn back in the virtual shopping mall, enter a shop and buy an item. Two hint buttons (e.g. List and Bag) were provided to allow users to view some hints during the shopping task. The operation of buttons was recorded automatically, and outputted as a log file after finishing the test. In addition, this system output event signals when users entered/exited the shop, bought an item, and checked the shopping list. fNIRS data was also recorded with these signals.

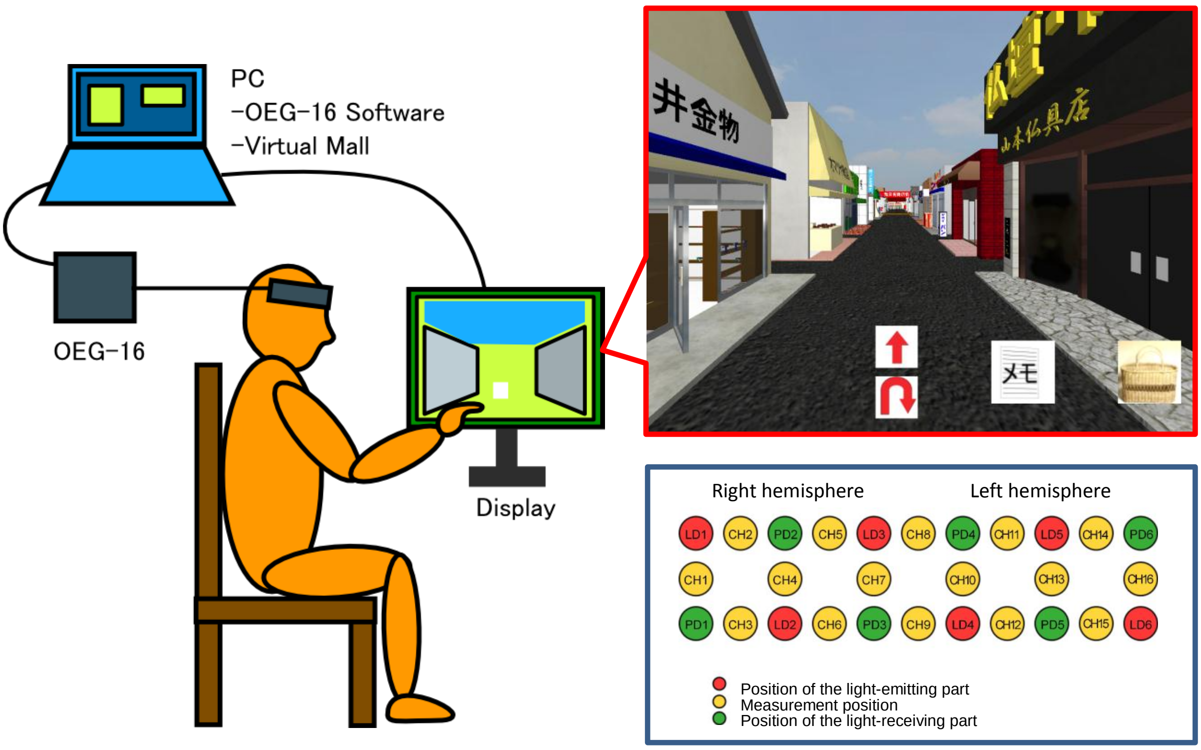
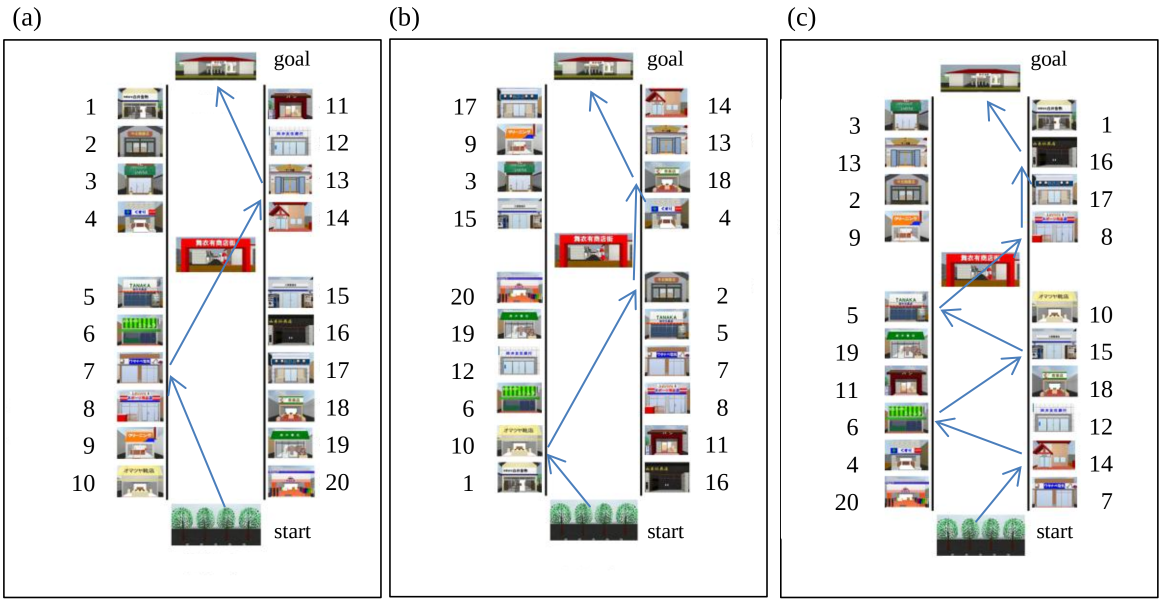


Figure 1. *Experimental system with VST-R screen and fNIRS channel arrangement on the forehead.*

The fNIRS system was used at a sampling time of 0.65 seconds, the intensity of the light detected at two wavelengths, 770 and 840 nm, was measured, and changes in the optical density were calculated. The system then calculated changes in the concentration of oxygenated hemoglobin [oxyHb], deoxygenated hemoglobin [deoxyHb], and total hemoglobin [totalHb] based on the Beer–Lambert approach. Emission and detection probes were bilaterally attached to the forehead of each subject. The detection probes were set at Fp1 and Fp2, which corresponded to the international 10–20 system of electrode placement with emission probes. Channels covered the bilateral PFC.

2.1.1 Task setting. We constructed a virtual shopping mall in a virtual space, and set up three different tasks with different difficulties. Figure 2 shows three kinds of map and shopping list used in each task. The virtual shopping mall used in each task had twenty shops and a train station, whereas the arrangement of these shops in the mall differed between tasks. The bottom of the map was the start point, while the top was the goal. Task 1 asked subjects to buy two specific items, Task 2 asked them to buy four specific items, and Task 3 asked them to buy six specific items on each shopping list. Subjects had to search the shops that sold specific items and select the target item from six items inside the shop. The blue arrow routes mean the most efficient shopping order in Figure 2.



<Shopping list >
- a pudding
- AAA-sized batteries

<Shopping list >
- tomatoes
- rubber boots
- an alarm clock
- a teacup

<Shopping list >
- an eraser
- plum liqueur
- incense sticks
- building blocks
- an 80-yen stamp
- a baseball glove

1: hardware store, 2: chinaware shop, 3: flower shop, 4: pharmacy, 5: stationary shop, 6: toy shop, 7: electric appliance shop, 8: sporting goods shop, 9: laundry, 10: shoe store, 11: bakery, 12: bank, 13: candy store, 14: post office, 15: liquor shop, 16: Buddhist altar fittings store, 17: watch store, 18: fruit and vegetable shop, 19: bookstore, 20: tailor's shop

Figure 2. *Maps of the shopping mall and shopping lists used in each task: (a) that for Task 1, (b) that for Task 2, and (c) that for Task 3. The blue arrow routes showed the most efficient shopping order.*

2.1.2 Experimental procedure. The subjects were first asked to memorize the specific shopping items while looking at the shopping list for 10 seconds. They were then allowed to plan the shopping routes that they considered to be the most efficient by filling in a blank map sheet with a pencil. They were asked to buy the specific items as quickly and efficiently as possible, while minimizing the use of hints. They were allowed to refer to a blank map at any time during the VST-R.

2.1.3 Outcome variables. VST-R had eight outcome variables: the number of times subjects used each button on the screen (Bag use, List use, Forward movement, and Reverse movement), the number of items bought correctly (Correct purchases), Total time, Time in the shops, Time on the road, and those could be calculated from the recording data automatically.

2.2 Data Collection

2.2.1 Participants. Seven brain-damaged inpatients with cognitive dysfunctions in the convalescence rehabilitation ward and six young healthy subjects participated in this study. The participant characteristics were presented in Table 1. Patients included some forms of brain damage experienced within six months from onset. The participation criteria for the patients were as follows: 1) cognitive ability to understand how to operate a touch screen and 2) physical ability to reach and touch the screen by their uninvolved upper limbs. The study exclusion criteria were as follows: i) severe aphasia, and ii) severe unilateral spatial neglect. All participants received written and verbal information about the study and gave written informed consent. The protocol of the study was approved by the Kobe University Graduate School of System Informatics Ethic Committee and Nishi Memorial Port Island Rehabilitation Hospital Ethic Committee.

Table 1. *Participant characteristics.*

	Patients (n=7)	Healthy subjects (n=6)
Gender (M: F)	4: 3	4: 2
Age	62.0 ± 19.3	23.2 ± 1.0
Duration of education (years)	14.9 ± 1.7	16.8 ± 1.0
Disease duration (days)	102 ± 54.3	—
Diagnosis	stroke: 3 traumatic brain injury: 2 encephalitis: 2	—
MMSE	27.4 ± 1.7	—

M: male, F: female, MMSE: Mini-Mental State Examination

2.2.2 Procedure. All participants were administered VST-R in the order of Tasks 1, 2, and 3 and questionnaires concerning subjective assessment after each task. The questionnaire consisted of three questions concerning the degree of task difficulty, the effort required, and psychological load. Each answer was rated on a five-point scale (1-5). Higher scores indicated higher load task. Patients also performed seven conventional neuropsychological tests and two questionnaires. The general cognitive level was evaluated using the Mini-Mental State Examination (MMSE). Attention was evaluated by the Symbol Digit Modalities Test (SDMT) (Smith, 1991) and Simple Reaction Time Task (SRT) (Beck et al, 1956). Regarding visual inattention, the presence of USN was assessed by Star and Letter Cancellation Tasks (Ishiai, 1999). Everyday memory was assessed using the Rivermead Behavioural Memory Test (RBMT) (Wilson et al, 1985) and Everyday Memory Checklist (EMC) (Kazui et al, 2006). Executive function was evaluated by the Zoo Map Test and Dysexecutive Questionnaire (DEX) (Wilson et al, 1996). All tests were finished within one month before and after the execution of VST-R.

2.3 Data analysis

We reset the data at the two points when subjects start to memorize shopping items and perform VST-R for fNIRS data analysis. We used a low pass filter (cut-off frequency 0.05 Hz and attenuation slope 40dB/Oct). We used Ch4-6 data as the right PFC (rPFC), Ch7-10 data as the medial PFC (mPFC), and Ch11-13 data as the left PFC (lPFC). The average change in [oxyHb] in each PFC area was calculated for memorizing phase: while subjects memorized the shopping items, and VR phase: while they operated the touch screen and were in a shop and on the road in the virtual mall. A task difficulty level (Task 1, Task 2, Task 3) × group (patient, healthy) ANOVA was conducted for behavioral data analysis. Descriptive statistics were also performed in this study due to the small sample size.

3. RESULTS

3.1 Cognitive assessment in the patients

The cognitive assessment data of the patients was presented in Table 2. They all had difficulties in their instrumental activity of daily living. The cognitive dysfunctions were related to more than one aspects of ability: attention, memory, and executive function.

Table 2. *Patient characteristics in cognitive assessment.*

Cognitive test	median	the minimum - the maximum
Attention		
SDMT (%)	30	17 - 42
SRT: correct rate (%)	93.8	68.8 - 100
Star cancellation task /54	54	51 - 64
Letter cancellation task /40	37	35 - 39
Memory		
RBMT: standard profile score /24	14	9 - 22
EMC /39	12	2 - 25
Executive function		
Zoo Map Test: the 1st trial /8	5	0 - 8
Zoo Map Test: the 2nd trial /8	8	4 - 8
DEX /80	8	1 - 41

3.2 Behavioral data

A comparison of VST-R performance between the two groups was presented in Figure 3 and 4. All seven patients accomplished Task 1, six patients could do Task 2, and five patients could do Task 3. A patient who needed the longest time (552 seconds) to complete Task 1 got lost in the mall and bought the same item twice. Another patient did not complete Task 2 by using hints and the map efficiently and needed some assistance from a tester. The number of purchases in each task was not sufficient or excessive for some patients. The mean numbers of Bag/List use and Forward/Reverse movement were larger in the patients than for the healthy subjects in all tasks.

The mean time required to complete the task was longer for the patients than for the healthy subjects in all tasks. The results of ANOVA showed a significant main effect of Task difficulty level and Group at the time required, but no interactions, except for that of the Task difficulty level × Group interaction with Time in the shops. The Total time and Time on the road were longer in Task 3 than in Task 1. Time in the shops in Tasks 2 and 3 was longer in the patients than in the healthy subjects. However, there was no main effect and no interaction for other variables.

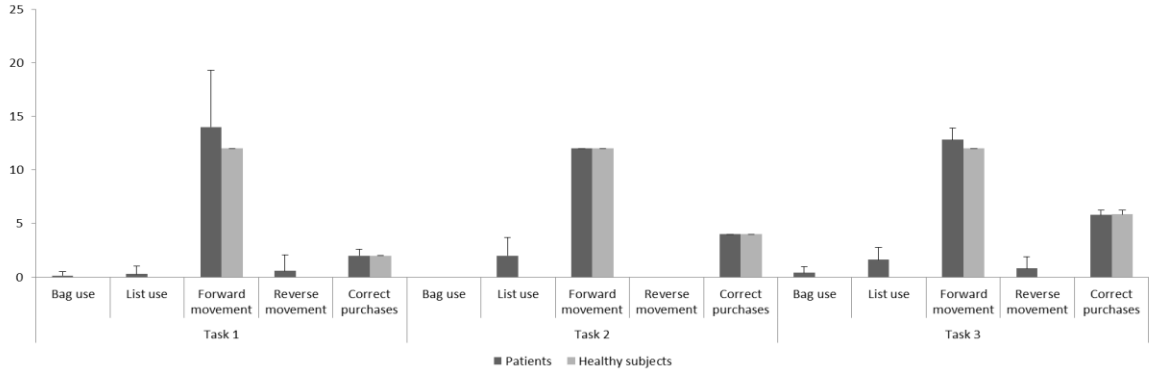


Figure 3. *Comparison of VST-R performance between the patients and healthy subjects (1).*

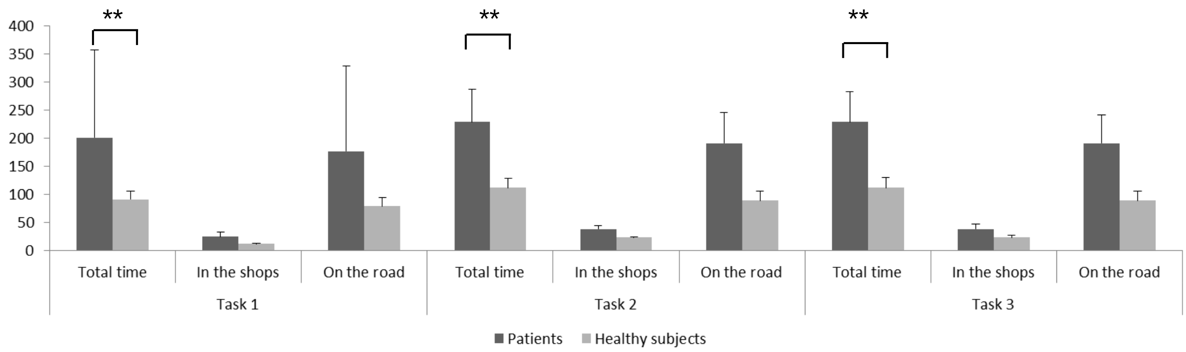


Figure 4. *Comparison of VST-R performance between the patients and healthy subjects (2). ** p < 0.01*

3.3 fNIRS data

Figure 5 shows mean changes in [oxyHb] (Δ[oxyHb]) in each area of PFC in the two groups. We analyzed data obtained in four patients and five healthy subjects in consideration of small artifacts and an older age range for the patients. In the patients, Δ[oxyHb] increased in rPFC in Task 1, increased slightly in mPFC in Task 2, and increased in all PFC areas in Task 3 in the memorizing phase, while it decreased largely in Tasks 1 and increased in Tasks 2 and 3 in all PFC areas in the VR phase. In the healthy subjects, Δ[oxyHb] increased in rPFC in Task 1 and increased in all PFC areas in Tasks 2 and 3 in the memorizing phase, while it increased in r/lPFC in Task 1, increased in rPFC and decreased in mPFC in Tasks 2 and 3 in the VR phase.

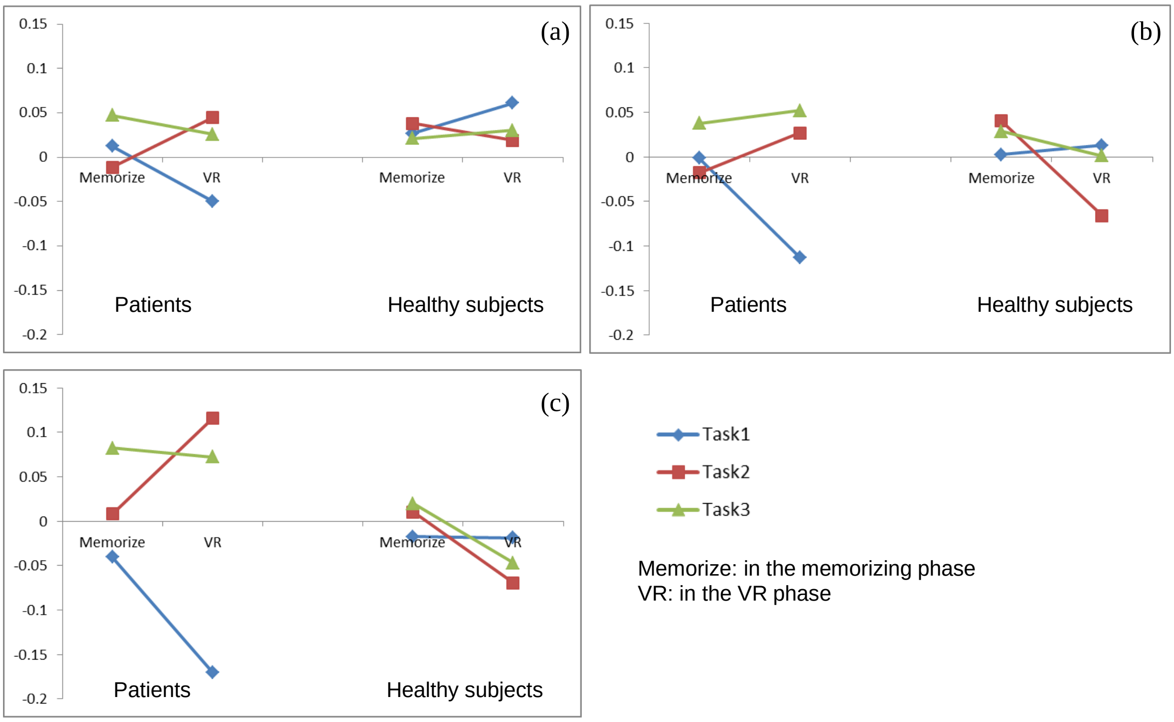


Figure 5. *Mean changes in the concentration of oxygenated haemoglobin in each PFC area: (a) right PFC, (b) left PFC, and (c) medial PFC.*

3.4 Subjective Assessment

The comparison of subjective assessments between the two groups was presented in Figure 6. Higher scores indicated a higher load task. All three assessment items were higher for the patients than for the healthy subjects in each task. The mean scores were higher for the patients than for the healthy subjects in all items. The mean scores on *task difficulty* were 3.0 ± 0.6, 3.9 ± 0.7, 4.0 ± 1.2 for the patients and 1.2 ± 0.4, 2.5 ± 0.8, 3.7 ± 0.5 for the healthy subjects (Tasks 1, 2, and 3, respectively). The mean scores on *efforts made* were 2.9 ± 0.9, 4.1 ± 0.7, 4.4 ± 0.5 for the patients and 1.2 ± 0.4, 2.3 ± 0.5, 3.7 ± 1.0 for the healthy subjects, respectively. The mean scores on *psychological load* were 3.0 ± 1.0, 3.9 ± 0.7, 3.4 ± 0.9 for the patients and 1.2 ± 0.4, 2.2 ± 1.0, 3.0 ± 1.4 for the healthy subjects, respectively.

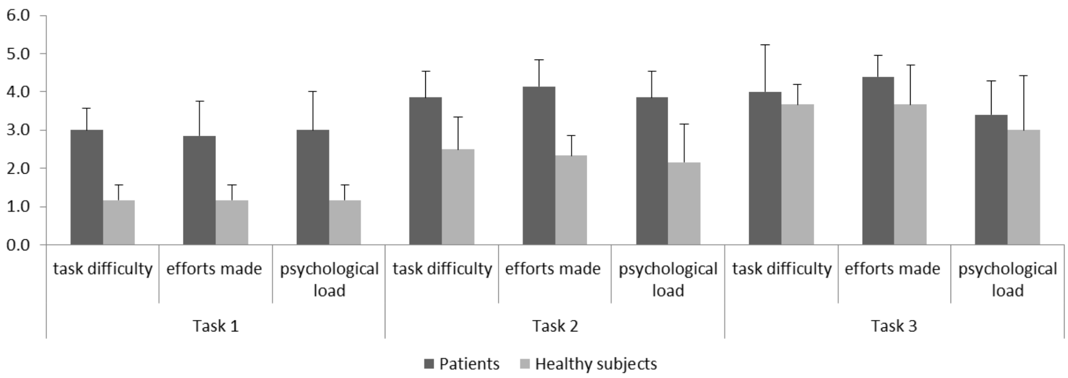


Figure 6. *Comparison of subjective assessments between patients and healthy subjects.*

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4. DISCUSSION AND CONCLUSIONS

The objective of this study was to investigate differences in task performance, brain activation and subjective assessments in relation to different task difficulty levels in convalescent brain-damaged patients and healthy young adults.

Regarding the VST-R performance, some patients could not accomplish Tasks 2 and 3. We considered they should start exercise from this difficulty level. One old patient needed more time to accustom herself to the virtual mall and its operation. A comparison between the two groups revealed that the mean time required to perform the test was significantly longer for the patients than for the healthy subjects. We considered that VST-R variables, including the number of correct purchases and the total time were important for cognitive assessment. On the other hand, some times when the list was used were regarded as natural behaviour; therefore, and it may be possible to use VST-R in memory rehabilitation with useful compensation strategies.

Regarding brain activation, the pattern of brain activation was particularly different between the two groups in Tasks 1 and 2. Small difference was observed in Δ[oxyHb] in each task for the memorizing phase between the two groups; however, Δ[oxyHb] in the VR phase in Task 1 in all PFC area was lower and it in Task 2 was higher in the patients than in the healthy subjects. These results also suggest that the difficulty levels of Tasks 2 and 3 may have been sufficient to cause brain activation in the brain-damaged patients in this study. Since our sample size was small, we need to amass more data with patients with similar diagnosis and investigate brain activation in relation to the task level in more detail in our next study. In healthy young adults, small increases were observed in Δ[oxyHb] in only right PFC in all tasks for the both phases. It indicated that even 6-item shopping task did not reach their upper limit.

Regarding subjective assessments, patients considered all tasks to be more difficult and required a stronger effort than the healthy subjects. The patients had a subjectively heavier psychological load in Tasks 1 and 2 (2-item and 4-item shopping task) than healthy adults. In addition, although the healthy subjects could recognize the differences between the three task levels, the patients could not. Therefore, we consider that therapists should take subjective mental load on patients into consideration because it may be important to evaluate changes in the exercise phase for more effective rehabilitation.

The results of the present study suggest that, although large differences were not observed in the task performances or PFC responses of healthy subjects at different task levels, they could recognize the differences between the three task levels subjectively, whereas the patients could not, and this indicated that the patients could not subjectively distinguish differences in the three tasks. VST-R is applicable to convalescent patients with higher brain dysfunctions in cognitive rehabilitation, and performing a 4-item/6-item shopping task activated their PFC especially in the interacting with VR environment phase. The easiest 2-item shopping task may be applied clinically by taking into consideration their behavioral errors and mental load.

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