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Cognitive Function Evaluation Utilizing Information Mismatch in Virtual Reality: An Exploratory Investigation

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Abstract

Cognitive Function Evaluation Utilizing Information Mismatch in Virtual Reality: An Exploratory Investigation

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The purpose of this dissertation was to investigate information mismatch in virtual reality (VR) and explore the possibility of using the cognitive reaction arising from information mismatch for cognitive evaluation. The virtual kitchen task was used to observe the subjects' behaviors while performing the task, and to investigate the characteristics of movement and cognitive processes appearing during the performance of the virtual task. In addition, an attempt was made to explore the factors of cognitive overload in VR that determine the difference compared to a performance in the real environment. In particular, this study aimed to investigate how information mismatch occurring in VR causes cognitive overload in terms of sensorimotor control.

First, it questioned how the cognitive process in VR differs from the real environment and also investigated the factors affecting the performance of tasks in VR. In the young adult group, while there was a significant difference between the execution time in VR and in the real environment in the difficult kitchen task, there was no such difference in the easy kitchen task. Meanwhile, among the elderly, there was a significant difference between the execution time in VR and in the real environment regardless of whether the task was difficult or easy. It was thought that cognitive load was caused due to difficulties in sensorimotor control in VR. It was found that the cognitive capacity is challenged when the task is difficult because the load of task performance itself and the load of sensorimotor control are doubling.

Second, it was found that as the cognitive function decreased, an abrupt and jerky movement pattern was exhibited during the virtual kitchen task. The number of sequences in movement until the task was completed was also busier in the elderly group with lower cognitive function in contrast with those with higher cognitive function. In the case of the elderly with deteriorated cognitive function, it is suggested that there is difficulty in minimal jerk movement control because the predictive ability responding to environment is decreased. In addition, according to the results of multiple regression, cognitive function of the elderly is the most influential factor in performing VR tasks, other than age and educational background, which means that purely evaluating cognitive function may be suggested.

Third, an attempt was made to verify how the unpredictability of sensorimotor feedback causes cognitive load in VR. The reaction time and speed of movement depending on the predictability of perturbation were measured in implicit 5 degrees and explicit 15 degrees perturbation. When the subject was unable to predict the variation of perturbation only in implicit motor control, reaching became slower and it took more time due to the accuracy and speed trade-off. In other words, unpredictability due to information mismatch leads to the use of different cognitive strategies in brain mechanisms.

In conclusion, VR induces more cognitive load than the real environment because the sensory feedback is unpredictable and variable due to technical fidelity problems. The sensorimotor control in VR is challenged by the way the human motor system is adapted. Further, it was found that an unpredictable environment requires different cognitive strategies for the sensorimotor system to adapt to it. The manner in which effective cognitive strategies are taken represents an efficient central executive function. From this perspective, VR-based cognitive evaluation, using such attributes, is thought to be an alternative method for early screening of cognitive decline.

Keyword : Elderly, Information mismatch, Predictability, Sensorimotor control, Virtual reality

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Preface

This dissertation was submitted to the Interdisciplinary Program in Cognitive Sciences at Seoul National University in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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CHAPTER 1. Introduction

1.1 Research Motivation and Introductory Overview

Virtual reality (VR) technology combined with a head mounted display (HMD) enables the construction of diverse and lively environments. It is attracting attention as a new ecological method of neuropsychological evaluation. Virtual tasks such as navigation, kitchen tasks, and shopping tasks were widely applied to evaluate the cognitive function of subjects for a diverse diagnosis. There is currently an insufficient explanation of how individual characteristics determine the performance level of a virtual task. It is necessary to study the factors that affect VR task performance. A

The mechanism of cognitive processes when performing VR tasks is different from when real tasks are performed. Further, there is cognitive overload in VR. It is required to understand how one perceives and interacts with virtual objects when they exist in a virtual world. Sensorimotor adaptation in the virtual environment is a key factor that varies cognitive load and consequently determines one's performance in virtual tasks. It is especially necessary to investigate the cognitive load depending on the predictability of visual feedback in the sensorimotor control process in VR.

In this dissertation, the aim was to investigate the characteristics of the cognitive process in VR. In particular, it was an attempt to investigate the cognitive load caused by sensorimotor control in a virtual environment and explore how VR can be used for cognitive evaluation.

1.2 Research goal and questions

1.2.1 Overall Research goal

The purpose of this study is to investigate the cognitive load caused due to mismatched information during sensorimotor control. Certain VR tasks were used in order to systematically manipulate such mismatched information, and an attempt was made to ascertain how cognitive load changes according to the inconsistency of information provided within the VR environment.

First, it was found how the cognitive process in VR differs from it in the real environment. Further, the factors that affect the task performance in VR were investigated. In addition, it was sought to verify how the unpredictability of sensorimotor feedback causes cognitive load in VR.

1.2.2 Research Questions

In this dissertation, the characteristics of the cognitive process in VR were investigated by asking the following questions along with an exploration of whether it can be applied to cognitive evaluation by utilizing the nature of cognition in VR.

Q1. Is there a difference between cognitive load in reality and VR?

Q2. What are the characteristics of movement in VR according to the cognitive function of the elderly?

Q3. What demographic factors affect the performance of VR tasks?

Q4. How does the predictability on sensorimotor feedback affect cognitive load in VR?

1.2.3 Research Contribution

The findings of this dissertation could explain the difference between the cognitive load in reality and VR. It was possible to find out how the characteristics of movement in VR were expressed according to cognitive function, identify the factors that impact the performance of elderly people in VR tasks, and define the characteristics of performance in VR according to cognitive functions.

It was also possible to understand the mechanism of cognitive overload while performing the virtual tasks in terms of sensorimotor control in VR, and also to explain how predictability of sensory feedback affects cognitive load from the perspective of the internal model for motor control.

Finally, it was found that a daily VR task can be suggested as a sensitive and ecologically valid paradigm to evaluate the cognitive function of the elderly.

1.3 Thesis structure

- **Thesis 1:** Differences between reality and VR-based tasks performance according to task difficulties in two different age groups

  In the young adult group, there was a significant difference in the execution time of the difficult kitchen task in VR and reality; however, the same did not hold true for the easy kitchen task. Meanwhile, among the elderly, there was a significant difference in the execution time of the kitchen task between VR and reality regardless of whether the task was difficult or easy. Therefore, it was shown that a greater cognitive load is required among the elderly to manipulate objects with the controller in VR.

- **Thesis 2:** Efficiency of movement trajectory and sequence in VR according to cognitive function among the elderly

According to the cognitive function of the elderly, it was found that an abrupt and jerky movement pattern was exhibited during the virtual kitchen task. In addition, they showed that the number of sequences appeared to be busier in performing tasks. Among the elderly with mild cognitive impairment, it is suggested that there is difficulty in minimal jerk movement control because the predictive ability responding to environment is decreased. It is necessary to identify the cognitive load required for predictive brain control in VR.

- **Thesis 3:** Effects of age, education, and cognitive function on the performance of immersive virtual kitchen tasks by the elderly

Individual variance in VR performance of the elderly group was greater than that among the young adult group. The most critical factors affecting an individual's performance were differences in age, educational background, and cognitive functions. Cognitive function was found to be the most influential factor among the elderly in performing VR tasks.

- **Thesis 4:** Effects of predictability of visual perturbation during the simple reaching task in VR

Another purpose of this study was to observe changes in cognitive load according to the predictability of visual perturbation when performing the simple reaching task in VR. It was found that the unpredictability of sensory feedback induces cognitive load in the sensorimotor control process. Motor control is a system that quickly adapts to perturbation. When unpredictable feedback was presented, a new cognitive strategy was adopted to increase the accuracy of the movement, and the movement speed slowed down. This phenomenon was found to be more pronounced in the implicit process of motor control. In conclusion, the uncertainty of sensory feedback due to visual perturbation in VR causes cognitive load to take a new cognitive strategy.

CHAPTER 2. Theoretical Background

2.1 Virtual Reality as Ecological Method for Cognitive Evaluation

Cognitive evaluation accurately identifies the level of cognitive function and provides an index for the functional level of daily activities. Sensitive and accurate neuropsychological results can suggest a starting point and direction for rehabilitation treatment for patients with cognitive impairment (Lezak, Howieson, Loring, & Fischer, 2004). Neuropsychological tests evaluate cognitive function by focusing on cognitive conceptual constructs to determine cognitive function according to the mechanism of the human brain. Although neuropsychological tests are based on robust conceptual constructs, the question remains whether the evaluated concepts authentically represent a person's cognitive function. Ultimately, someone's cognitive function might be more accurately reflected by behaviors in natural contexts, and this is a consideration of the ecological aspect of cognitive function. Thus, brain science has spent years developing neuropsychological evaluation as a research methodology and evaluation framework. Neuropsychological evaluation enables us to accurately assess the neurocognitive ability of patients with brain lesions and predict how cognitive deficits affect IADLs.

The first generation (1950–1979) of neuropsychological testing development established methods for defining cognitive symptoms consistent with brain lesions and diagnosing disease. The second generation (1980–present) has used information and computer technology (ICT) to develop more efficient evaluation methods by automating many of the assessment and scoring processes (Parson, 2015). Computerized cognitive evaluation has been widely used for efficiency because computerized evaluations are inherently consistent, and automated scoring and interpretation reduces bias and speeds the processes. However, computerized cognitive evaluations has dimensional limitations that reduce cognitive matter to only the most basic psychometric aspects (Riva, 1998). To determine a patient's cognitive ability, it is necessary to recognize the reaction that occurs during the evaluation process and to apply a flexible evaluation technique. As an alternative that can supplement the limitations of computerized cognitive evaluation, virtual reality (VR) technologies enable more sophisticated evaluations that can be adjusted according to a patient's responses.

The overriding question concerning computerized neuropsychological testing is whether the cognitive ability evaluations they produce accurately depict patients' functional cognitive ability. The disadvantage of the first-generation methods using paper and pencil and the second-generation methods using repeated stimuli response is that they do not include contexts rich in cognitive stimuli. For example, laboratory-based cognitive evaluations often differ from the patient's observed cognitive function and performance in daily life. In addition to ascertaining the validity and reliability of the cognitive evaluation constructs, we need to consider their veridicality and verisimilitude from an ecological point of view. Evaluation results that reflect real-life performance are more likely to aid in developing effective treatments.

Parson (2015) argued that the development of the third-generation neuropsychological assessment should be more ecological and use more advanced computer interfaces. However, the disadvantage of emphasizing the ecological aspect of evaluation and implementing evaluations similar to everyday life in the real-world environment is that such evaluations cannot be strictly controlled. This can lead to a lack of scientific rigor in neuropsychological testing. For this reason, some neuropsychologists have begun using VR technology, which enables them to combine realistic stimuli in real-world scenarios with controllable laboratory environments during cognitive evaluations.

Computerized cognitive evaluation has the advantage that it can be accurately implemented regardless of the evaluator's skill. In addition, providing an electronic stimulus has the practical advantage that the subject's response can be recorded automatically. Both 2D and 3D computerized cognitive evaluations have advantages over traditional manual methods, including consistency, efficiency, and convenience. However, 3D digital evaluations through head-mounted displays (HMDs) have an additional advantage. First, objects and probes are realized in 3D, giving a more immersive and lively feeling. In addition, VR compensates for the shortcomings of indirect computer interfaces requiring the use of manipulated devices (e.g., mouse, keyboard) by gathering data through natural actions such as walking or extending an arm. VR can reveal rich information about human behavioral characteristics by tracking and recording even the most subtle head and body movements.

The advancements in VR technology incorporating haptic technology and auditory and video feedback make users feel as though what they are experiencing is real. This perceived authenticity in VR suggests new possibilities for cognitive function evaluations (Riva, 1997). Research has reported that memory learning through HMD in a high-quality graphic environment offers superior immersion and task performance compared to 2D monitors (Murcia-López & Steed, 2016). Cognition is embodied cognition, which accumulates and monitors information through various somatosensory and multisensory inputs from the body, including visual information (Foglia & Wilson, 2013; Wilson, 2002). Therefore, VR environments create scenarios in which our motor systems can operate as they might in real life while providing more diverse stimuli.

VR environments effectively simulate real environments through wearable technology that allows complete immersion and interface-free operation. This allows neuropsychologists to set up controlled environments for observing human cognitive behavior. However, VR environments are limited by their fidelity to sensory stimulation and action feedback. Fortunately, VR engineering does not need to perfectly and completely create realistic scenarios; they only need to create the *perception* of reality. Thus, we need to know more about how the human cognitive system adapts to physical fidelity in VR and how it appears in performance.

2.2 Subtypes of VR Tasks According to Target Cognitive Functions

VR environments represent a novel scientific method for measuring human attention, visuospatial perception, memory, and executive function (Parsons, 2014; Riva, 1997). VR-based tasks have high veridicality and verisimilitude in neuropsychological testing because they allow patients to interact with the environment and move as they would in the real environment without manipulating a computer mouse or keyboard. In recent years, the easy-to-use wearable technology has been used for various dementia-evaluation studies (Fernandez Montenegro & Argyriou, 2017; Mendez, Joshi, & Jimenez, 2015).

Many simple tasks to evaluate human attention and body scheme function were proposed in the early stages of VR task development. Since then, more sophisticated spatiotemporal pathfinding tasks have been proposed (Ijaz et al., 2019; Zakzanis et al., 2009). These immersive VR-based tasks open up new possibilities for evaluating cognitive function, episodic memory, and executive function (Allain et al., 2014; Ouellet, Boller, Corriveau-Lecavalier, Cloutier, & Belleville, 2018; Plechatá, Sahula, Fayette, & Fajnerová, 2019; Raspelli et al., 2012; Widmann, Beinhoff, & Riepe, 2012).

2.2.1. VR task for spatial navigation

Spatial navigation requires complex cognitive functions. The spatial navigation function requires functions that include allocentric and egocentric representations, spatial organization, and memory (Lithfous et al., 2013). Older age is associated with functional decline in selective cognitive performance, anatomy, brain function, and wayfinding (Moffat, 2009). Loss of navigational skills is a prominent feature in the early stages of Alzheimer's dementia.

Spatial navigation is different from tracing a route on a 2D map of a real environment. Many researchers have developed an interest in immersive spatial navigation tasks using VR. (Immersive VR has more realistic image refresh rate and field of vision than non-immersive VR.) Ijaz et al. (2019) evaluated the compatibility and feasibility of using an immersive VR platform to assess older adults' spatial navigation memory by comparing it with a standard PC-based (SPC) screening platform. Using the VR-CogAssess platform integrating an Oculus Rift HMD and immersive, photorealistic imagery, they asked 42 older adults to identify six landmarks as they navigated on a map. When they used the PC platform, they had to indicate direction using the arrow keys on the keyboard. In contrast, when they used the VR system, they could indicate direction by simply turning their heads. The VR group showed higher scores and fewer pathfinding errors than the SPC group in the landmark recall test, landmark identification quiz, and self-report test. Immersive VR had the dual advantages of excluding computer proficiency and hand mobility and simulating pure space-time search ability.

VR-based navigation tasks can be useful for screening patients with early-stage Alzheimer's dementia. Zakzanis et al. (2009) used an immersive virtual environment to verify whether age-related and cognitive-related factors caused differences in path learning and memory. After four learning sessions, they asked eight young adults and seven elderly subjects to perform a navigation task using HMD targeting. Immediately after that, the participants completed a recognition test on buildings and objects in the city. They were tested again 20 minutes later. The young adult group found the route faster and more accurately than the elderly group in both the immediate and the delayed test conditions. The elderly patients with mild Alzheimer's disease had the lowest performance and the most errors in the landmark-identification task.

Task performance in VR shows a significant correlation with actual performance. Cushman et al. (2008) tested the validity of VR evaluations by comparing the real and VR wayfinding performances of 35 young normal adults, 26 normal elderly people, 12 people with a mild cognitive impairments (MCIs), and 14 people with early-onset Alzheimer's disease. All the groups performed the same navigation task in the real environment and the VR environment. There was a close correlation with task defects. Compared to young adults, the other groups showed low performance in both conditions on the self-orientation and scene localization tasks, and the MCI and early Alzheimer's group showed deficits in the verbal recall task. These results suggested that VR tests could provide a reasonable alternative to other methods for evaluating age- and Alzheimer's-related decline.

2.2.2. VR task for memory

There are various types of memory. Explicit memory is divided into semantic and episodic memory. Clinically, neuropsychological evaluations and treatments generally focus on semantic memory. However, episodic memory disorders are common in the early stages of some dementia subtypes, such as Alzheimer's (Hornberger & Piguet, 2012). One method for evaluating episodic memory in clinical practice involves reading or hearing a story, then recalling its contents (Choi, Lee, Kim, & Kim, 2006).

Widmann et al. (2012) investigated whether there was a difference in daily memory between a healthy elderly group and a mild Alzheimer's group using a VR environment simulating the real one. They evaluated the degree of memory for linguistic elements and spatial scenes. The VR testing revealed memory impairments in the patients with Alzheimer's that classic list-recall tasks had not revealed.

Since memory operates in a dynamic context, VR's ability to simulate infinitely variable, richly detailed environments makes it invaluable for memory evaluations. The number of sensory stimuli and information to be processed can make VR simulations more cognitively challenging than traditional tests. VR environment can be useful for screening dementia patients and distinguishing MCIs. Plancher et al. (2012) evaluated episodic memory using VR in patients with amnesia-type MCIs and early mild Alzheimer's disease. They immersed healthy older adults, patients with amnestic mild cognitive impairment (aMCI), and patients with early to moderate Alzheimer's disease in two different VR experiences: driving a virtual car and being a passenger in a virtual car. They asked the participants to memorize information and then complete recall and recognition tests. The patients with Alzheimer's, those with MCIs, and the normal elderly group had the worst performances, in that order. The spatial allocentric memory test was particularly useful for differentiating MCIs in the normal elderly. The VR test performances showed a higher correlation with the patients' subjective daily memory problems than the conventional memory tests, confirming the construct validity and suggesting that VR could be a viable alternative for initial diagnoses and rehabilitation monitoring.

The shopping task is often used for evaluating episodic memory (Ouellet et al., 2018; Plechatá, Sahula, Fayette, & Fajnerova, 2019; Widmann et al., 2012). Plechatá et al. (2019) conducted a grocery shopping task with a group of normal adults and elderly persons using HMD in an immersive virtual supermarket environment. They found no difference in the adult group's memory test performance between the two platforms. However, the elderly group showed more memory errors when using the HMD platform.

Similarly, Ouellet et al. (2018) implemented an immersive virtual environment and scenario, Virtual Shop, to evaluate episodic memory in normal and elderly adults and test the scenario's applicability and ecological construct validity. The research investigated the difficulty and level of interest in the virtual shop task. Both groups performed adequately, exhibiting neither the ceiling nor the floor effect. The elderly group recalled fewer items and had longer task completion times than the normal adult group, suggesting that the VR task could enable sensitive assessments of age-related differences in episodic memory. Previous research results have shown that VR-based memory evaluation can help practitioners identify memory differences between normal adults and normal elderly people. However, more research needs to be done to determine what appears to be age-related differences in memory capacity really reflects an inability or unwillingness to adjust to VR technology.

2.2.3. VR task for executive function

Executive function, the most complex and highest cognitive function, includes such basic cognitive processes as planning, performing, monitoring, and correcting human actions (Lezak, Howieson, Loring, & Fischer, 2004). The frontal and prefrontal cortices have primary control over executive function. Executive function cannot be fully evaluated using pencil-and-paper tests or self-reports on behavior problems in daily life; traditional neuropsychological tests are insufficiently sensitive and ecologically valid (Jansari et al., 2014). Thus, previous studies have used goal-oriented, multistep shopping, kitchen, errand, and office tasks to test executive function in VR settings (Allain et al., 2014; Krch et al., 2013;

Parra & Kaplan, 2019; Plechatá et al., 2019).

Evaluating executive function requires analyzing the task performances' accuracy, execution time, movement characteristics, and errors (Giovannetti et al., 2002, 2019). Parra and Kaplan (2019) investigated differences in task performance between young and elderly adults using a 2D non-immersive errand task. In the multiple error test, they gave the participants one minute to memorize a museum map and then write down information about five exhibits in a given location. They found no difference in the task-performance accuracy between the young and elderly adults, and both groups traveled significantly longer distances in the real environment than in the VR one. This might be because there were more obstacles and stimuli (and distractions) in the real environment.

Researchers at the Massachusetts of Technology (MIT) developed the virtual multiple errands test (VMET) (Raspelli et al., 2012; Cipresso et al., 2014). Raspelli et al. (2012) investigated the ecological validity and initial construct validity of the VMET for evaluating executive function by comparing the VMET and traditional neuropsychological test performances of post-stroke patients, healthy young adults, and healthy elderly adults. The correlation between the two tests was significant. The VMET test enabled the researchers to observe distinctions between the post-stroke and healthy patient groups and healthy young and elderly adult groups, confirming that the VMET had ecological validity and construct validity. There is a difference in task completion in errand tasks according to cognitive function, and the distance moved is different for each task. Parra and Kaplan (2019) noted that conducting errand tasks in real environmental contexts could introduce too many complexities and other people, adding confounding factors that affect the efficiency of the movements. However, some studies have shown that the distances traveled in VR were greater than in the real environment. Overall, studies' conclusions regarding the total distances traveled in VR versus real environments have been inconsistent.

Perhaps a more critical consideration than the amount of movement or distance traveled is the movement sequencing and pauses because these variables represent the effectiveness of the cognitive functions. Werner et al. (2009) compared the performance differences between the patients with mild cognitive impairments and normal elderly adults using the virtual action planning supermarket (VAP-S) too. The group with MCIs took longer to complete the VAP-S test, stopped more, traveled longer distances, and displayed more inappropriate behaviors than the normal elderly group, suggesting executive function problems.

Cipresso et al. (2014) conducted four different tests with 15 individuals with Parkinson's disease (PD) with MCIs (PD-MCI), 15 with Parkinson's with normal cognition (PD-NC), and 15 cognitively healthy adults. In one test, the participants used VMET to select and purchase products in a virtual supermarket to detect early defects in executive function in patients with PD. The PD-NC patients had more errors using VMET than the normal control group, with a poor ability to use effective strategies to complete the tasks. The VMET results seemed to be more sensitive in the early detection of executive function deficits than the Mini–Mental State Examination (MMSE), clock-drawing test, and Tower of London test.

Another common errand-task type is kitchen tasks, such as making coffee, setting the table, and packing a lunch. Allain et al. (2014) investigated the usefulness of non-immersive virtual coffee tasks (NI-VCT) with patients with Alzheimer's dementia. Compared to the healthy elderly control group, the Alzheimer's group performed lower on all tasks. NI-VCT measurements were significantly correlated with all other neuropsychological measurements in the correlation analysis. In addition, regression analysis showed that NI-VCT performance was a good predictor of actual work performance and IADL function as reported by caregivers. These results support the effectiveness of using virtual kitchens for IADL evaluation in Alzheimer's patients.

Using the Schwartz et al.'s (2002) Naturalistic Action Test (NAT) in a VR task, Giovannetti et al. (2002) analyzed the behavioral error types that occur during tasks performance, categorizing them as errors of omissions (e.g., failing to close a container or turn off a stove) or commission (e.g., sequence errors, misorientation, substitutions, or repetitive actions). Giovanetti et al. (2019) implemented a NAT inspection virtual environment inspection and collected preliminary data. They conducted cognitive tests on elderly and young adult groups, assigning them the task of preparing breakfast and lunch in a virtual kitchen challenge (VKC) with virtual objects and touch screens and a real kitchen with real objects. They obtained automated performance measurements from the VKC program and manual ones from the real kitchen, scoring both. The elderly group made more errors than the young adult group in both the VKC and the real kitchen, showing similar error patterns across the measures. The VKC's automation measures correlated significantly with the developer measures, real-world kitchen performances, and cognitive test scores, suggesting that the VKC could be used to efficiently measure people's IADL difficulties for clinical and research purposes.

2.3 Factors Affecting VR Performance

2.3.1. General

When applying VR tasks as an alternative to traditional cognitive evaluations and rehabilitation treatments, there are several considerations given that most target groups are patients or the elderly. Factors affecting task performance in VR environments include gender, age, academic background, cognitive function, mobility, and past work history (Oliveira et al., 2018; Plechatá et al., 2019). Previous studies have identified age and cognitive function as the most influential factors in VR task performance, with more cognitive decline noted among the elderly than the young adults. Patients with cognitive impairments encounter greater difficulties in VR task performance than control groups. Thus, when considering VR tasks' feasibility as an evaluation tool for screening cognitive function, we need to rule out the influence of other confounding factors. For example, some studies have suggested that there are gender-related differences in VR task performance. Cutmore et al. (2000) investigated the gender factors influencing path learning with a VR maze-finding task, examining the results according to activity, passivity, gender, and cognitive style. They found that the male participants more readily acquired path information through the landmark than the female participants. Whether because of some innate difference or sociocultural conditioning, the male participants focused more on the VR environment’s spatial relationships and analytic structures , and the female participants focused more on image clarity and interactions. The participants with the highest proficiency in spatiotemporal recognition had the highest performance. During the VR path learning task, the right cerebral hemisphere was more active than the left. Cutmore et al.’s (2000) study confirmed the usefulness of path learning in a VR environment for training or and testing spatiotemporal processing and imagery.

Educational attainment is highly correlated with cognitive function (Kim et al., 2014; Mortamais et al., 2014). One recent study found that even when there is neurophysiological cognitive deterioration, differences in the level of cognitive reserve affect the time it takes to appear at the functional level (Farina et al., 2018). Thus, some forms of dementia could be prevented by sensitively screening for the early stages of cognitive deterioration. Cognitive degeneration sometimes first appears as directly observable performance inefficiencies in IADLs long before cognitive function deterioration has begun causing problems. Thus, VR-based tasks could provide cognitive challenges of varying difficulty levels, acting as a kind of cognitive treadmill for measuring cognitive capacity. The following paragraphs summarize the literature on VR task performance according to age and cognitive function.

2.3.2. Age effects on VR performance

Plechatá et al. (2019) investigated whether there was an age-related difference between 2D and HMD performance in a virtual supermarket shopping task (memory task). For the young adults, the error rate was similar regardless of the task method. However, the elderly adults committed more errors when using the HMD than the 2D monitor. The researchers found a platform-based difference in the execution order. When the participants used the 2D monitor first, their subsequent HMD performance was worse; however, when they used the HMD before the 2D monitor, there was no difference in their two performances. Perceiving and performing tasks using an HMD requires high-intensity cognitive function—a higher cognitive load. Therefore, the results suggested that when the participants used the HMD after the 2D monitor, their mental fatigue caused their subsequent (HMD) performance to deteriorate.

Parra and Kaplan (2019) investigated whether there was an age-related difference in distance traveled and task performance accuracy in non-immersive tasks. The differences in the virtual accuracy, real accuracy, virtual distance, and real distance between the young adults and the elderly adults were not statistically significant. There was no difference in the task-performance accuracy between the VR and the real environments for either group, but there was a difference in distance. Both the young and elderly adults covered more distance in the real National Museum of Scotland than in the VR version. They concluded that there were more distractors and attractors in the real museum. Thus, it was difficult to accurately evaluate the participants' cognitive function according to the cognitive load of the task due to the uncontrolled confounding variables. They noted that virtual accuracy was the strongest predictor of real accuracy and vice versa, explaining 73.19% of the variance (a large effect size). However, the statistical significance of the correlation between the distance covered in the VR and real environments was difficult to explain. They also could not fully explain the statistical significance of the correlation between the task accuracy and distance covered. However, they found that the elderly participants' visual perceptions and IADLs significantly predicted the distance they would travel in the VR and real environments. This suggested that the elderly participants' cognitive decline was reliably observable in the VR task.

2.3.3. Cognitive challenges in VR

Zakzanis (2009) conducted an immersive spatial navigation task in a VR forest of city buildings. He found that the participants with Alzheimer's dementia and reduced cognitive function showed more memory errors in the VR pathfinding task than the healthy elderly. He found age-related differences in completion time and navigational errors but not distance traveled. The distances traveled by the young and elderly adults were similar. This might be because the elderly were more likely to conserve energy to accommodate any deteriorations in their physical function, giving them sufficient time to plan their movements (Kirasic et al., 1992). However, the elderly adults with cognitive impairments covered more distance because there were more unplanned movements than planned movements.

Cushman et al. (2008) used real and nonimmersive VR environments to compare the differences in patients' wayfinding task performance. In ascending order, they found that young adults, healthy elderly adults, adults with MCIs, and adults with dementia had different performances between the real environment and VR tasks. In each subtest of the navigation task, the score in the real environment showed the same pattern as the score in the VR environment. This suggested that VR could be a valid tool for evaluating spatial navigational skills—and a more sensitive tool for decreasing cognitive function. Patients with Alzheimer's frequently exhibit prominent cognitive deficits involving spatial navigation (Deipolyi et al., 2007). We often see visuospatial and navigational problems in the early stages of dementia and the transition from MCI to dementia (Mapstone et al., 2003). Therefore, spatial navigation it is an important cognitive function for detecting the pathology of MCIs, although it can be difficult to evaluate it safely in everyday life. VR environments offer a controlled way to test spatial navigation without placing patients at undue risk.

2.3.4 Feasibility of VR tasks for assessing dementia

Neuroimaging findings in dementia diagnoses complement neuropsychological assessments. People in the early stages of dementia often experience problems with executive function (Knopman et al., 2001; Voss & Bullock, 2004). Therefore, evaluating executive function through the IADL performance can help screen for early dementia. When there are deficits in executive function, those affected have problems performing such real-life tasks as developing strategies, planning, engaging in online monitoring, inhibiting irrelevant stimuli, and formulating responses (Crawford, 1996; McGeorge et al., 2001).

VR has also been used in treating patients with dementia. Distinguishing the subtype and severity of dementia is necessary to determine the best therapeutic direction and slow or prevent neurodegeneration by optimizing cognitive function (Flynn et al., 2003). Continuous cognitive stimulation and task performance in real daily life environments can help, but it is difficult to organize the environment to suit the therapeutic purposes systematically. Thus, properly configured VR environments could help evaluate and train dementia patients' cognitive ability to provide focused tasks and block distracting stimuli.

Dementia manifests as a complex set of cognitive impairments. For this reason, dementia is referred to as a state of pervasive cognitive decline. Recent dementia research has described the dementia state as a "loss of self." Dementia interferes with both voluntary and pre-reflective (subconscious or habitual) movements and behaviors (Kontos, 2004). Flynn et al. (2003) examined the feasibility of treating patients with dementia using VR, measuring their physical and psychological well-being objectively by recording their heart rate during the VR sessions and subjectively with questionnaires and real-time prompts. They found that the patients perceived the VR experiences as real and generally felt in control of their interactions, experiencing no significant increase in symptoms, simulator sickness, or other problems. Their findings supported the use of VR environments with patients with dementia. VR environments can provide safe, fun, and stimulating environments for patients with dementia and can help alleviate their volition-less symptoms and encourage them to remain active (Hodge et al., 2018).

2.4 Cognitive Load in VR

2.4.1 Immersive vs. non-immersive VR

VR refers to a world created using real-time 3D images created by a computer system. It also refers to a virtual world where people can interact, navigate, and move. VR uses many transmission forms, such as HMDs, PCs, mobile devices, workstations, cave automation virtual environments (CAVEs), large screen systems, and virtual tables. To date, VR research has mostly been based on nonimmersive platforms, but more research should be done on the feasibility and clinical utility of immersive VR-based evaluations. A literature review by Strong (2020) found only three studies assessing dementia using immersive VR-based assessments.

Because it uses real-time image refresh rates and vision fields, immersive VR feels more “real” and allows more natural behaviors than non-immersive VR. VR can also make people feel claustrophobic stuffy because VR using HMD cuts users off from the real world. It can also have side effects, such as dizziness or vomiting. However, the increased vividness of the graphics and the realistically wide field has led to greater acceptance of HMD-based VR. One study found that the tendency to reject the idea of HDM-based VR increased with age, but their attitude and inclination to use it increased after experiencing VR just once (Huygelier et al., 2019).

Studies have found that people perform better on memory tasks using immersive VR environments than with 2D screens (Plechatá et al., 2019; Ventura et al., 2019). Technological advancements in HMDs provide fully immersive, 360-degree experiences that users perceive as real. Of course, it is possible to present 360-degree panorama scenes on 2D PC monitors or tablets, but the physical separation and surroundings detract from the immersion; with HMDs, the users experience only what they “see,” hear, feel through the headsets (Ventura et al., 2019).

Recent VR studies have found performance and qualitative differences in immersive versus non-immersive VR environments. Plechatá et al. (2019) found that the performance error rate between 3D and 2D was similar for young adults, but elderly adults made more performance errors in the 3D immersive environment. The differences between the two environments depended on the tasks’ difficulty. For the elderly adults, there was no difference in the error rates between the immersive and non-immersive VR environments when there were few items, but increasing the number of items in the task also increased the error rate. In contrast, there was no difference for the young adults in the error rates between immersive and non-immersive, regardless of the number of task items (Plechatá et al., 2019). The elderly adults had more difficulty performing tasks in the immersive VR environment than the young adults. Plechatá et al. (2019) surmised that increasing the cognitive load by adding numerous sensory inflows through the HMD made it more difficult to process the target task. The performance between young and elderly adults differed depending on the type of platform used. However, the younger adults performed better than the elderly adults in the VR scenes, suggesting that age-related cognitive decline and performance changes could be detected using virtual assessments.

There are several reasons why the elderly often find it difficult to perform tasks in immersive VR environments. First, both real environments and immersive VR environments generally present large quantities of information to be processed. However, people are familiar with “reality.” No matter how realistic the virtual environments might be, they are just different enough to add additional cognitive load. VR environments with abundant sensory stimulation are themselves a distraction in cognitive processing. Thus, the “strangeness” of the VR experience can overload people who have impaired cognitive processing (more common in the elderly), requiring additional cognitive functions to suppress the distractions so they can perform the target behavior (Allain et al., 2014; Parsons & Rizzo, 2008).

Second, sensorimotor control is difficult for people interacting with objects using a VR controller. Motion manipulation in VR is qualitatively different from motion manipulation in real life. The characteristics of the generated action differ, as do the feedback of the visual and somatosensory senses for the action. For example, suppose you are performing the task of spreading jam on bread in a VR kitchen. The spreading and buttering motions require active supination and pronation in the real environment but are replaced by touching motions in virtual reality. How well you cope with the motion substitution in VR depends on how much experience you have with VR experiences and movements. Young adults who have never performed HMD-based VR tasks adapt to the experience more readily than elderly adults with no HMD-based VR experience.

In general, a more vivid sense of presence seems to improve memory input and retrieval in immersive VR environments. Users who directly experience or have a vivid sense of reality with the VR find it easier to remember the experience and for longer periods. Ventura (2019) found that when people performed memory tasks in an immersive VR environment with a 360-degree full panorama view, their memory recognition results were better than non-immersive environments. When executing two consecutive tasks, with the first in a non-immersive environment and the second in an immersive environment, the second experience reinforced the memory trace in the memory recollection task. (Serino & Repetto, 2018).

Makransky et al. (2019) investigated using VR as a learning tool for science classes. They found that the students considered the classes more realistic and impressive when the experience was immersive but the higher cognitive load decreased actual academic performance as the students were unable to concentrate on learning (Makransky, Terkildsen, & Mayer, 2019). Because VR environments differ from our real environments, they add to the cognitive load used to engage in activities. Given that the results differ depending on whether the VR environment is boosting or distracting for cognitive operations, we need to know more about the cognitive operation mechanism in VR environments.

There are different brain-activation patterns for high- and low-immersion VR. Pfurtscheller (1989) found that cerebral cortex activation increased in high-immersion environments, and event-related desynchronization increased in the alpha band (8–13 Hz). Furthermore, fMRI research indicates that the negative connectivity of the DLPFC and the parietal region increases in immersive VR situations (Baumgartner et al., 2008). Kober et al. (2012) found that highly immersive 3D VR environments induce interactive activation in the cortical network connected from the parietal region to the frontal region compared to the 2D environment.

2.4.2 Sense of presence and situated cognition

The sense of *presence* describes the feeling of being present in the VR environment. It comes from perceptually reacting to objects and changing environmental stimuli in VR. *Immersion* and *presence* have different operational definitions. The *immersion* concept can be explained from a systematic point of view: immersion describes how similar the VR environment is in sensory terms to the real environment, indicating how real users perceive its objects to be (Slater, 2003). The immersion concept is based on the characteristics of humans' external environment. Many previous studies on VR development have used high-resolution, full-range panoramic displays to increase fidelity and created more immersive VR systems using auditory, tactile, and haptic feedback (Cooper et al., 2018). A highly immersive VR is one with realistic, multisensory stimuli and feedback. The higher the degree of fidelity, the higher the level of immersion in VR (Slater, 2003).

In contrast, *presence* refers to the perceived degree of immersion—the sense of whether users feel that they exist in the VR environment (Slater, 2018). Presence is more related to the users' subjective thoughts than the characteristics of the external environment. Therefore, even at different levels of immersion, users can feel the same presence; conversely, even at the same level of immersion is provided, individuals can feel a different presence (Slater, 2003). Slater (2018) emphasized that the sense of presence can be thought of as the belief that the VR environment could be real but also the realization that it is not. Thus, we need to think more deeply about what a sense of presence means in reality. Presence is the result of a perceptual system that processes stimuli in VR. When the motor action induced by the perceptual system precedes the cognitive judgment ("this is not real"), users feel the sense of real presence (Slater, 2018). The sense of presence is high when the natural sensorimotor contingencies for perception in VR are similar (O'Regan & Noe, 2001; Slater, 2018). Therefore, to realize VR environments that feel more like real environments, we need to understand the mechanisms that process the sensory stimuli in VR and the cognitive science of the responding sensorimotor controls. By penetrating and reflecting the cognitive understanding within the VR environment, we could implement VR environments with ultrahigh fidelity and create more realistic VR environments.

Building on Damasio (1999), Riva, Waterworth, Waterworth, and Mantovani (2011) and divided the sense of presence into three levels. The lowest level, the *proto presence*, involves mostly unconscious proprioception, where users think, “I am in this space where I am currently located.” The second level, the *core presence*, involves semiconscious perceptions of what is real and what is not; the richer the information and visual cues used for sensory processing, the stronger the sense of presence. At the core presence level, the VR environment creates an environment intentionally by adjusting environmental cues, which is why dementia treatment using augmented reality (AR) can help improve patients’ IADL performance. The third level, *extended presence*, involves a conscious conceptual understanding where users sense that they are in a space by linking meaning and relevance from past memories to present information. The normal sense of presence processing in VR involves anticipating what will happen while processing what is currently happening based what has happened in the past. Therefore, dementia patients find this difficult because their memory impairments remove the experiential reference, so they might not experience the same sense of presence in VR environments (Garcia, Kartolo, & Methot-Curtis, 2012).

2.4.3 Sensorimotor adaptation in VR

Motor control includes the process of repeatedly re-representing motor commands by receiving sensory information about the current state of the body and environment (Bays & Wolpert, 2007). Sensory feedback can be inaccurate and add variable noise. Because we cannot anticipate all the sensory feedback from the next motion, we can experience errors between the predictive representation and the updated representation in the context of uncertainty. These errors add noise to the sensory-processing system. Sensorimotor control reduces these errors. Our nervous system integrates and uses information from our multiple senses to reduce the uncertainty in sensory feedback. Cross-referencing information from multiple senses can reduce errors caused by single-sense input. We need to integrate vision and proprioception to understand our bodies’ current locations and control our motor functions. Predictive filtering allows us to reject incoming sensory information with little value (Bays & Wolpert, 2007; Todorov, 2004).

The cognitive load changes in the process of reducing sensory noise and creating optimal integration in the sensorimotor control process. The higher the noise variability and uncertainty, the more cognitive operations are required for sensorimotor control. Thus, we can view VR as a condition where technical problems can cause a conflict between visual feedback on the position of our VR hand and proprioceptive feedback on our actual moving hand. The brain's continuous need for error correction to account for the discrepancy between two separate sensory inputs increases the cognitive load.

Taylor and Ivry (2011) proposed a set-point model including descriptions of individual characteristics to optimize visuomotor strategies. In their model, users easily give up on unacceptable strategies and seek new ones with fast time intervals to reduce target errors (Taylor & Ivry, 2011). If the prediction for the selected action is incorrect, users implement a new strategy immediately. This process occurs in the middle of a moving trajectory (Taylor & Ivry, 2011). Sensorimotor control is regulated according to categorical strategy conversions while being controlled online in real time.

2.5 Sensorimotor control in VR

2.5.1 Predictive brain and internal model for motor control

The predictive brain reduces prediction errors in the calculation process between the prediction of motion at the beginning of perception and the sensory feedback from the senses (Clark, 2013). Top-down and bottom-up processing occur in both directions simultaneously, and prediction and error correction repeat iterative processing in the hierarchy at each step—what Daniel et al. (2019) called *perceptual inference*. The prediction mechanism is equally applicable to behavior. Cascading predictions trigger motions, and the brain checks information matches against the constantly and continuously incoming sensory feedback. This process predicts the next step in a sequence connected to each sub-step (Hawkins & Blakeslee, 2004). The regularity of the sequence is important because it determines the prediction and the load of the mismatched sensory feedback.

Our brains plan and produce an output (response or action) using an internal model of the movement. At this time, the internal model is divided into forward and inverse models. We send the motor commands created by our brain to the related body part, and at this time, we create an efference copy of the created internal model to create a forward model. The forward model calculates the error between the predicted body position and the actual body position and reduces the error. The forward model operates the process of predicts the next state based on the motion command and current state. The difference from the expected result produces a newly adapted movement command through the chewing of the cud (Blakemore, Wolpert, & Frith, 2002). On the other hand, the inverse model estimates the motion control required to convert the current arm position to the desired position by inputting the initial desired position. The combined model of the forward and inverse models has significant advantages in motion command and control. When the actual feedback and the predicted feedback do not match, the error detection and correction processes are activated.

It is possible to move more precisely through real-time monitoring and correction. This can be explained using the *forward model*, which makes an efferent copy that predicts the sensory result for motor commands, then recalls the information by comparing it with the actual movement. Finally, the results can differ depending on the noise. Being able to arbitrarily adjust the noise value in a VR environment can broaden its research and experimentation value.

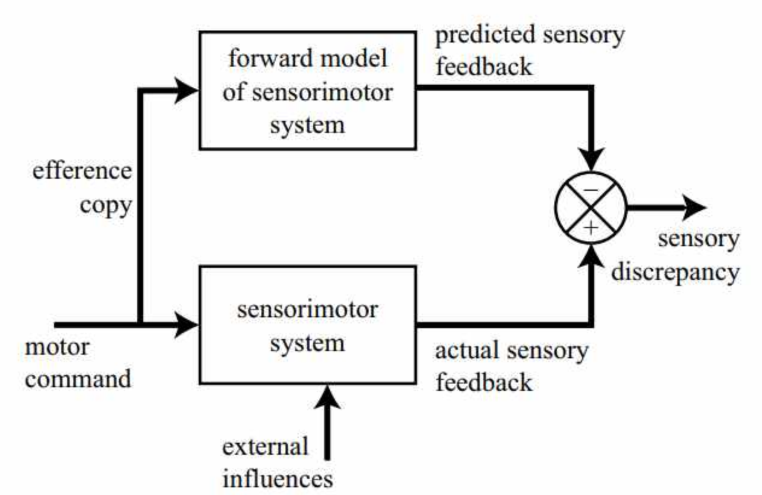


Figure 1. Forward model in motor control (adapted from Beers, Baraduc, & Wolpert, 2002)

The uncertainty of sensory feedback affects the cognitive load for sensorimotor control (Van Beers, Baraduc, & Wolpert, 2002). Noise-affecting uncertainty can be divided into sensory and motor noise. In sensory noise, the perception of an object's position is uncertain because of the noise in the sensory information (Van Beers et al., 2002). When the noise in sensory and movement processing increases, the brain requires additional cognitive processes to minimize uncertainty about movement.

2.5.2 Explicit and Implicit Sensorimotor Control

Implicit learning is controlled by prediction errors and calculations of the difference between the intention and the post-action feedback. This concept is in contrast to the *target error*, which is the calculation of the difference between the intended target and the post-action feedback. In implicit learning, motor learning is controlled by prediction error (Taylor & Ivry, 2011). Explicit learning is target-error-based learning. Cognitive strategies are taken through the interplay between implicit and explicit processes (Taylor & Ivry, 2011).

The motor system establishes strategies to reduce errors by calculating the predictive state and prediction error of the visual feedback. This works in the internal model. The prediction errors act and adapt quickly. The strategy for movement reduces errors within a short time and allows motor learning to occur (Taylor & Ivry, 2011; Taylor, Krakauer, & Ivry, 2014).

2.5.3 Accuracy and Speed Tradeoffs in Cognitive Control

Motor control takes place in two different learning time courses. *Motor learning* occurs quickly, and sensorimotor learning occurs slowly. Fast-adapted motor learning decays quickly, and slow-adapted motor learning decays slowly. Sensorimotor learning uses a trial-and-error strategy, leading to motor adaptation. The brain adopts new strategies after receiving feedback from the current control strategy.

The fast process occurs through explicit learning, and the slow process occurs through implicit learning. In elderly adults, both the fast and slow processes frequently become degraded (Wolpert & Flanagan, 2016). Therefore, they face significant challenges for their sensorimotor control in VR environments. Moreover, unpredictable and irregular sensory feedback can increase the cognitive load because it requires switching strategies to fit the situation. The unpredictability of sensory feedback on sensorimotor control can increase users' cognitive load in VR environments.

Feedback variability increases errors and the reaction times necessary to make the next operation accurate (Gritsenko & Kalaska, 2010). The accuracy and speed trade-off mechanisms work in movement (Wolpert & Flanagan, 2016). Even in our daily lives, when we move, if the feedback about the movement is predictable and regular, we can increase the speed of our movements without additional efforts to control the error. However, if the feedback on our movement is unpredictable, we need slow and accurate control to reduce errors, which slows the overall process. The sensorimotor system adopts this dynamic motor strategy to minimize the variability of this feedback (Wolpert & Flanagan, 2016).

2.6 Executive control for information mismatch in information processing

Functional brain function imaging studies have shown that the rostral areas of the anterior cingulate cortex (ACC) respond to the emotional aspects of error monitoring. In contrast, the dorsal and caudal areas of the ACC have various functional roles. They are known to be responsible for the attentional shift to meaningful stimuli in processing visual stimuli (Weissman et al., 2003; Orbetta et al., 1993). They are also known to play a role in monitoring processing conflicts. Parallel brain processing can be considered an efficient method for processing large quantities of information simultaneously. However, if there is a mismatch between meaningful (or not-yet-processed) information or information that needs to be filtered or inhibited, the brain needs a mechanism to detect and assign attention (Weissman et al., 2003). Due to the inconsistency in the two information processing processes, reaction disadvantages appear through task paradigms such as the Eriksen flanker task, Stroop task, and Navon task. The main conflicting information processing is between irrelevant perceptual and semantic representations. The ACC detects conflicts due to information mismatches and transmits the information to the prefrontal cortex (PFC) to activate it (Kerns et al., 2004). The PFC plays a role in executive cognitive control. A high cognitive load is associated with error detection and behavioral adaptations to respond to these errors.

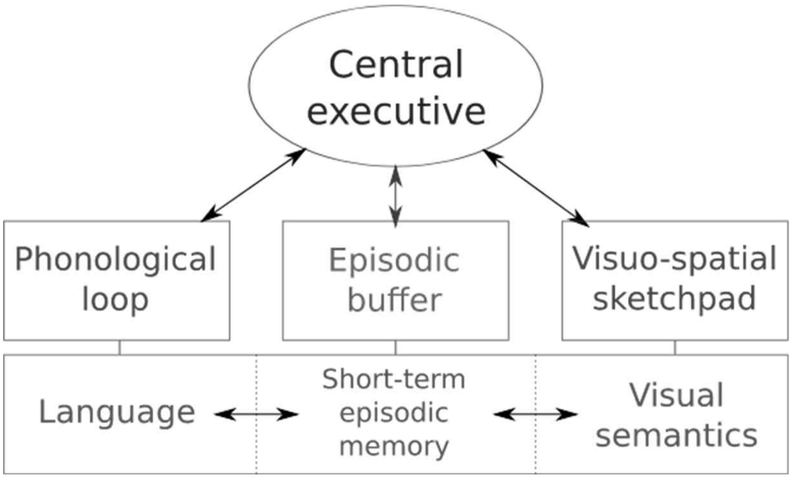


Figure 2. Baddeley's working memory model and central executive (adapted from Baddeley, 2000)

The concept of the central executive was proposed by Baddeley & Hitch in 1974 and is mainly related to the frontal lobe and explains that it plays a role in coordinating the operation of the slave systems (Baddeley & Sala, 1996). In the working model theory, it is explained that the central executive selects between two different sub-mechanism which are the phonological loop and visuo-spatial sketchpad. However, Normal and Shallice (1980) expand the concept of executive control as a Supervisory Attentional System (SAS). It is a related system for control of action and two different sources for perception and behaviors. Monitoring and regulating information mismatch generated from the sensory and action process requires executive control.

CHAPTER 3. Differences in Cognitive Load Between Real and VR Environment

3.1 Introduction

In recent years, virtual reality (VR) has become one possible approach for ecologically valid assessment of cognitive function (Ouellet et al., 2018; Parsons, 2014). Many VR-based assessment and rehabilitative interventions have been developed due to the diverse advantages of VR itself, that is, it can create various therapeutic contexts and multisensory environments. In addition, the use of immersive VR has been expanding through commercial head mounted display (HMD). Compared to the non-immersive VR, which had limitations due to computer interface discomfort, since immersive VR with HMD enables real action and behaviors, it is proposed as an alternative method for assessments (Plechatá et al., 2019). VR with HMD increases the sense of immersion and induces a perceptual experience similar to being in the real environment. By observing how humans behave and adapt in a VR environment, the ecological validity of cognitive evaluation can be increased (Allain et al., 2014; Parsons, 2014).

The advantages of immersive VR assessment can be summarized in some respects. First, it is possible to observe subjects' cognitive decline while performing activities of daily living (ADL) by easily constructing a virtual living environment. It is cost-effective to implement a low-cost evaluation environment, although the development cost itself has not yet reached the level of commercialization. In addition, another advantage is that it can also prevent accidents that may occur during real risky resources and environments for patients with cognitive deficiencies.

Recently, as an evaluation method for diagnosing dementia patients, researchers have been conducting VR-based cognitive function assessment or daily life evaluation (Fernandez Montenegro & Argyriou, 2017; Ijaz, Ahmadpour, Naismith, & Calvo, 2019; Mendez et al., 2015). Dementia patients often complain of problems with memory, spatiotemporal perception, and executive functions in daily life.

Among them, the inefficiency of executive function in the daily life of early dementia patients is often reported by family members or caregivers (Giebel, Sutcliffe, & Challis, 2015; Voss & Bullock, 2004).

Executive function is the most complex and highest cognitive function to motivate to do, plan, action, monitor, and correct human action (Lezak, Howieson, Loring, & Fischer, 2004). Executive function is particularly highly related to the pathology of the frontal and prefrontal lobes. Recently, the American Academy of Neurology (AAN) emphasized the importance of investigating the profile of executive dysfunction to rule out subtypes of dementia and screen out mild cognitive impairments in the way of dementia (Knopman et al., 2001; Voss & Bullock, 2004; Werner, Rabinowitz, Klinger, Korczyn, & Josman, 2009). It is most accurate to estimate executive function deficits through problems that appear in actual occupational performance; therefore, evaluation using the VR environment is useful to assess executive function for these reasons (Werner et al., 2009).

In the latest research on developing VR to evaluate executive functions, certain kinds of task such as the shopping, kitchen work, errands, office work, and so on were frequently used to challenge executive function in VR (Allain et al., 2014; Cipresso et al., 2014; Krch et al., 2013; Parra & Kaplan, 2019; Plechatá et al., 2019; Raspelli et al., 2012). These kinds of VR task were commonly characterized by being goal-oriented and requiring a series of steps.

In fact, previous VR studies have shown that mild cognitive impairment (MCI) and dementia patients perform poorly in VR when compared with the healthy elderly (Garcia et al., 2012; Tarnanas et al., 2013; Werner et al., 2009). It was also found that MCI patients take a longer time to perform or exhibit inefficiency in a moving trajectory when compared with healthy elderly people (Werner et al., 2009). Performing tasks in an immersive VR environment requires more cognitive load than would be required in the real environment. The elderly feels more cognitive fatigue to process the abundant sensory stimuli in VR (Plechatá et al., 2019). Besides, VR with rich cognitive stimulation is more challenging for MCI or dementia patients than for healthy elderly people. Action deficits such as errors, omissions, and perseverations seen in VR are prominent features in dementia and same pattern of deficits appear in MCI as well (Tarnanas et al., 2013). It means that performing in VR is sensitive in detecting problems in the early stages of cognitive decline.

In the consistency context, it was found that the difference in error when performing the virtual coffee task was larger than in the real environment between the healthy and demented elderly (Allain et al., 2014). In other words, the performance differences in VR between the two groups is larger than in the real environment. The reason can be summarized in two ways. The first is that more sensory information needs to be processed simultaneously to process presence in VR. In addition, it is thought that it is because additional sensorimotor processing is required for action adaptation in VR (Garcia et al., 2012; Slater, 2018). For these reasons, the elderly with cognitive deterioration may commit performance errors more frequently than the elderly with high functional cognition. In conclusion, VR is more sensitive in detecting cognitive deterioration and efficacy than performance in the real environment for the elderly population.

The kitchen task is feasible for examining the executive function in the dynamic context that interacts with the objects and environment because tasks require a series of steps and the maintenance of the goal to accomplish. For instance, "The Kitchen Task Assessment" (Baum & Edwards, 1993) was standardized and predicts the degree of cognitive deterioration and functional decline during the task well. Observing task performance in a real environment is highly correlated with neuropsychological test results. According to previous studies, performance in kitchen tasks were correlated with memory and executive functions to some extent (Baum, Edwards, Yonan, & Storandt, 1996). The Naturalistic Action Test (NAT), which was developed by Schwartz, is also one of the observation-based assessments to detect cognitive behavioral errors during kitchen work for patients with deficits in central nervous system (Schwartz, Segal, Veramonti, Ferraro, & Buxbaum, 2002). In particular, it has been reported that early-stage Alzheimer's patients exhibit everyday action deficits through the NAT kitchen task performance (Baum & Edwards, 1993; Giovannetti et al., 2002). Performing the kitchen tasks requires a lot of materials to prepare and involves environmental risks that may occur such as using a knife or working with hot liquids. Implementing a kitchen with VR can solve these problems and reduce costs of environmental set-up. In addition, kitchen tasks are performed frequently in one's daily life compared to errands or office tasks. People are used to performing kitchen tasks regardless of their level of education and occupational history.

A non-immersive Virtual Kitchen Challenge (VKC) was implemented by borrowing the idea of NAT, wherein the performances in reality and VR were compared (Giovannetti et al., 2019). As a result, it was reported that the patterns of behavioral errors seen in the two environments are similar. The limitation of this study is that it was two-dimensional (2D) monitor-based and non-immersive; the point is that there are essentially differences in action planning comparing to a 3D immersive environment. It is necessary to compare the performance in the 3D immersive environment with those in the real environment.

Accordingly, the aim of this study was to compare the performance differences found in VR and the real environment during kitchen tasks. It especially focused on finding out whether the cognitive load varies according to task difficulty. In addition, it was investigated whether these effects are the same in two different age groups.

Performing tasks in VR requires a different re-adaptation from how we perceive and act in the real environment. Cognitive load is additionally used for re-adaptation in VR. It is a competition between the cognitive load required to perform a task and the cognitive load required to re-adapt to VR. Therefore, it was assumed that the more difficult the task is, the greater the performance difference between VR and the real environment. That is, in VR, the more difficult the task, the more the cognitive load used for VR readjustment. As it was expected that there would be difficulties in sensorimotor control within the VR environment according to age, the elderly were expected to be affected more by task difficulty than young adults.

3.2 Methods

(1) Participant

Total 46 subjects (22 younger, 24 older) had participated in this study. Mean age of younger adults was 23.1 (SD ±2.51; 16 females and 6 males) and the elderly was 67.0 (SD ±5.21; 18 females and 6 males) (Table 1). All participants were novice for VR contents, the personal history of VR use was screened at the stage of recruitment. They were all neurologically healthy and had no medical diagnosis history. The informed consent form was gained from all participants and they were paid a certain amount of fee for participation.

(2) Description of task

The kitchen tasks consist of two missions which were preparing coffee and making jam sandwich. The followed sub-sequences in order to perform two different tasks were describe in table 1. The task which is preparing coffee is simple and less sequential than making jam sandwich. The tasks were performed in both real and virtual reality environments which were equally set up. The order of performing environment was randomized for each subject.

Table 1. Sub-steps and sequences of making butter and jam sandwich and preparing coffee

Making butter and jam sandwich	Preparing coffee
1.Get the two slices of bread	1.Get the cup from the shelves
2.Gather utensils (eg. Knife, butter knife, dish)	2.Gather utensils (eg. tea spoon)
3. Take out butter and jam from refrigerator	3. Pour the brewed coffee into the cup
4. Spread butter and jam on the bread	4. Add the sugar in it and stir till it is melted
5. Put together the bread and cutting it in half	5. Serve at the table
6. Put the sandwiches in the dish	6. Clean up the working space
7. Serve at the table	
8. Clean up the working space	

(3) Experimental set-up

Experiments were conducted by alternately setting the VR environment and the real environment in a 4*5M laboratory space where natural and reflected light were controlled. HTC's VIVE Pro Eye was used for VR, VR display was 1440*1600 pixels, 90 Hz refresh rate and visual field was max. 110°. The virtual reality implementation was implemented based on unity, and the objects constituting the kitchen scene looked similar to real objects using polycon & animation to increase the immersion, and the objects in virtual reality were interactive using a hand controller such as grab, lift, move, cut and spread, pour etc. The size of the virtual reality space was matched with the real space, and all trajectory of the movement can be replayed by storing the coordinates of the movement in the virtual reality. When performing a kitchen task in a real environment, he wore a helmet with a vive tracker on his head and installed 3 Microsoft Azure Kinect DKs to track the movement in the real environment.

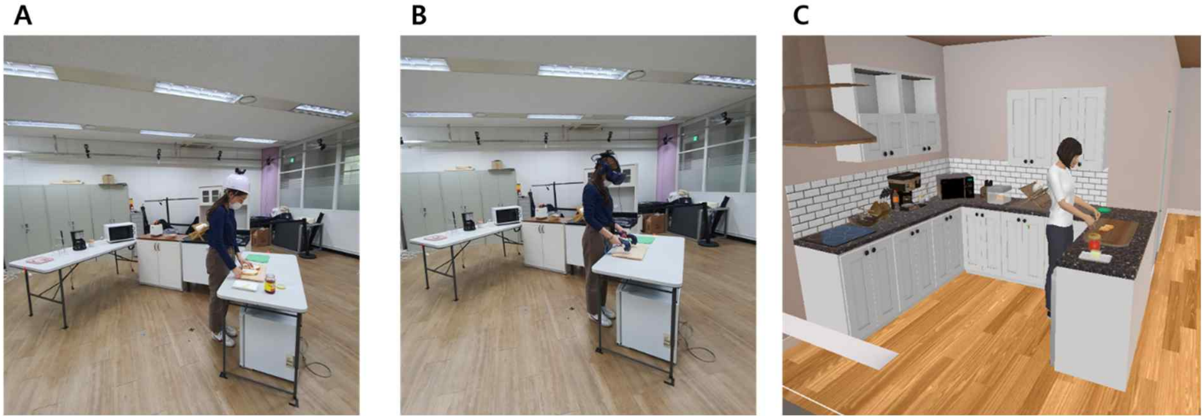


Figure 3. Experimental set-up. Performing kitchen task in real environment (A), in virtual environment with HMD (B), virtual scene (C)

(4) Procedure

Subjects performed the tasks of making jam sandwich and serving coffee once in virtual reality and real environment, respectively, and the order of execution was randomized for each subject. Before performing in virtual reality, the positions of objects in virtual reality were noted, and interactions with objects were practiced using a controller. Subjects performed and practiced the task once in a situation where a verbal cue of the experiment facilitator was given, and then proceeded with the main experiment. In the same way in all conditions, the start of the task started with the front facing the sink, and when the task was finished, they were instructed to return to the same seat and finish the task.

(5) Assessments

1. Korean Mini Mental State Examination (K-MMSE)

Korean version of Mini Mental State Examination (K-MMSE) was used to screen the general cognitive function in the elderly participants (Kang, Na & Hahn, 1997). It consists of items of time and place orientation, memory registration, attention and calculation, memory recall, language and spatiotemporal composition. The total score is 30 and the less than 24 is considered cognitive impairment. The dementia screening sensitivity of K-MMSE was .80 and the specificity was .70 (Oh, Kang, Shin, & Yeo, 2010).

2. Stimulator Sickness Questionnaire (SSQ)

SSQ is consisted of 16 items of symptoms which is evoked by virtual stimulator(Kennedy, Lane, Berbaum, & Lilienthal, 1993). The score is rated with Likert scale from 0(None) to 3(Severe). Sub-score system is divided with nausea related, oculomotor related, disorientation related items. Total score is summed of each sub-score in weighted value.

(6) Statistics Analysis

The statistics analysis was performed by using Jamovi 1.0.1.0 The age-related group differences were analyzed by Wilcoxon ranked test. Analysis of differences according to age, environment, task difficulty was conducted for statistical significance using three-way mixed design of repeated measure ANOVA.

3.3 Results

Mean age of younger group was 23.1 (±2.51) and older group was 67.04 (±5.12). The gender ratio between two group was similar, but the education level was originally different in younger and older group (*p*<.001) (Table 1). The average score of MMSE was 28.87(±1.11), so it is confirmed that the elderly who participated in this study were healthy and cognitively intact. History of VR use were surveyed with the short form questionnaire including experience with HMD frequencies of use. The previous experience of HMD use was not significantly different between two age group (*p*=.143). There were two persons who used HMD before in younger group, and the frequencies were less than 2 for the purpose of game and exhibition. On the other hand, there is no one to use HMD before in older group. The score of reported cyber-sickness by SSQ was 1.82(±2.75) in younger and 1.38(±2.16) in older group and they were not statistically significant.

Table 2. The demographic characteristics for each age group

		Younger (*n*=22)	**Elderly (*n*=24)**	**Group difference**	
				Mann-whitney U	*p value*
Age		23.10 (±2.51)	67.04 (±5.12)	0.0	<.001
Gender	**Male**	6 (27.3%)	6 (25%)	-	-
	Female	16 (72.7%)	18 (75%)		
Education		14.90(±0.97)	10.37(±3.32)	45.0	<.001
MMSE		-	28.87(±1.11)	-	-
HMD experience		0.19(±0.60)	0.00(±0.00)	219	.143
SSQ		1.82(±2.75)	1.38(±2.16)	243	0.605

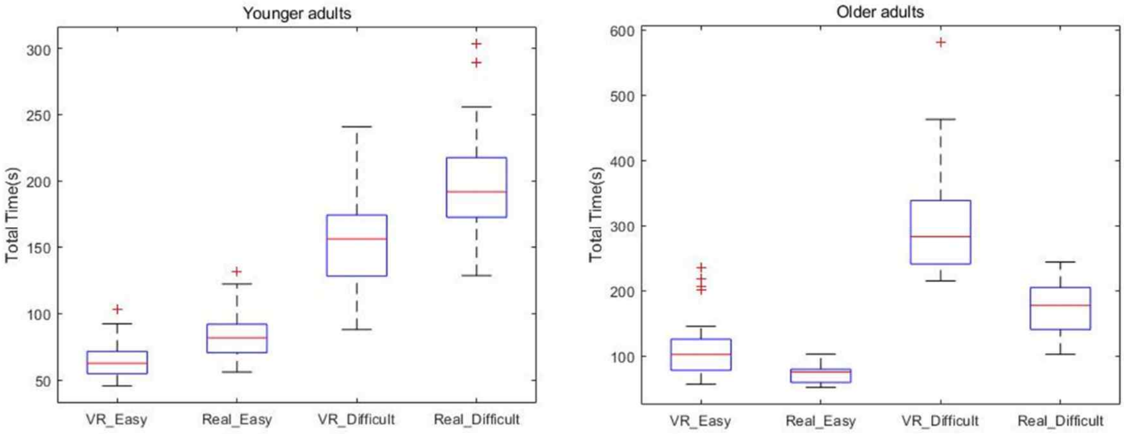


Figure 4. Plot for total time to perform the kitchen tasks in younger and older adults

The younger group spent less time in VR conditions but the older group spent less time in real conditions regardless of task difficulty (Figure 4).

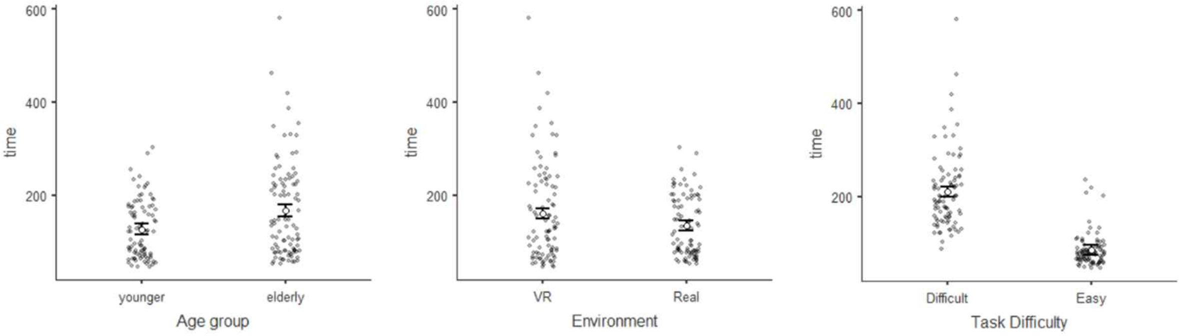


Figure 5. Jittered data according to age group, environment, task difficulty

It was found that the variance of the spent time for the task in the elderly group was larger than that in the adult group. The variance of the spent time for the task in VR is larger than in the real environment. The more difficult the task, the greater the variance of the spent time for the task (Figure 5).

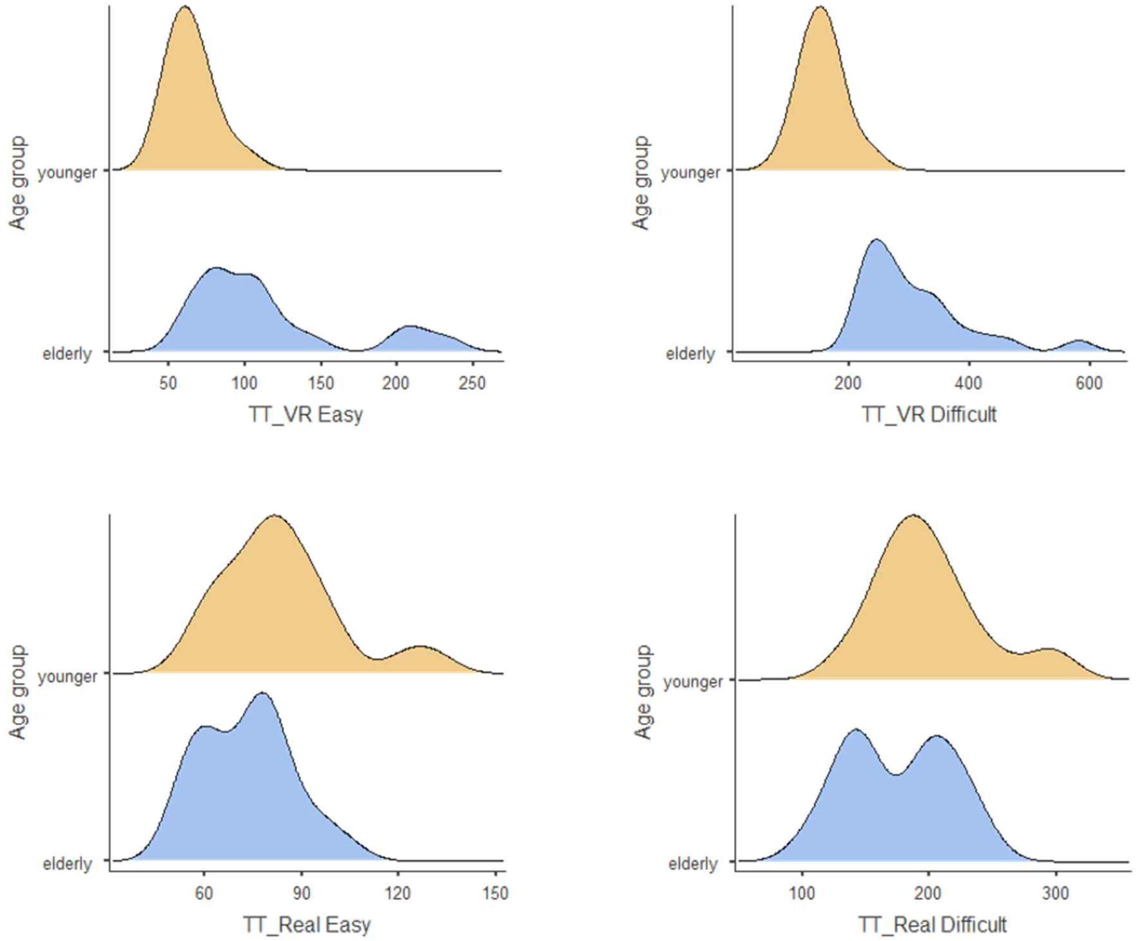


Figure 6. Density distribution of the spent time data in younger and elderly group (*TT: Total Time)

According to the density distribution, in the easy VR task, the young adult group showed a unipolar distribution whereas the elderly group showed a bipolar distribution (Figure 6). In the difficult VR task, both the young and the elderly group showed unipolar distribution. In the real environment, the young group showed wider distribution than VR environment. The bipolar distribution was shown both in easy and difficult task in the elderly.

Table 3. Results of repeated measure ANOVA according to age, environment, and task difficulty

	SS	df	MS	F	p	η^2_p
Between Subjects Effects						
Age group(A)	76877	1	76877	21.1	<.001	0.324
Within Subjects Effects						
Environment(E)	33593	1	33593	19.88	<.001	0.311
E ✻ A	157279	1	157279	93.09	<.001	0.679
Task Difficulty(TD)	717817	1	717817	459.19	<.001	0.913
TD ✻ A	21278	1	21278	13.61	<.001	0.236
E ✻ TD	11987	1	11987	9.58	0.003	0.179
E ✻ TD ✻ A	37150	1	37150	29.69	<.001	0.403

* SS: Sum of Squares; MS: Mean Squares

The main effect of age, environment, task difficulty was statistically significant [F(A)=21.1, F(E)=19.88, F(TD)=459.19, p<.001]. The interaction effect between environment(E) and age(A) was statistically significant [F(E*A)=93.09, p<.001] and the interaction effect between of task difficulty(TD) and age(A) was also statistically significant [F(TD*A)=13.61, p<.001]. As a result of Bonferroni *post hoc* test, there was a significant difference in the total time between VR and real in both younger and older group. There was a difference between difficult and easy task in both younger and older group.

For the last, there was the interaction effect among environment(E) * task difficulty(TD) * age(A) and it was statistically significant [F(E*TD*A)=29.69, p<.001]. As a result of Bonferroni *post-hoc* test, there is no difference between VR(M=64.4, SE=14.6) and real(M= 83.6, SE=18.5) when the task is easy, whereas there is a difference between VR(M=156, SE=34.8) and real(M=199, SE=43) when the task is difficult for the younger group. On the other hand, for the older group, there was a difference between VR(M= 114 , SE= 51.5) and real(M=72.9, SE=13.8) when task is easy and there is a difference between VR(M=305, SE=88.1) and real(M= 175, SE= 40.9) when task is difficult.

Table 4. Post hoc comparison for each condition

	Age group	Task difficulty	Environment	Mean	SE	$P_{bonferroni}$
Total Time	Younger	Easy	VR	64.4	14.6	1.000
			Real	83.6	18.5	
		Difficult	VR	156	34.8	0.008
			Real	199	43	
	Older	Easy	VR	114	51.5	0.011
			Real	72.9	13.8	
		Difficult	VR	305	88.1	<.001
			Real	175	40.9	

3.4 Discussion

As previously mentioned, this study implemented two kitchen tasks of different difficulties in VR and real environments to investigate whether there was a difference in performance depending on the environment and task difficulty. In addition, it was investigated whether performance differences between young adults and the elderly group appeared in a similar pattern. The kitchen task based on VR is useful in evaluating cognitive deterioration and the effectiveness of executive functions. When cognition deteriorates, it starts as a very small behavioral error and inefficiency in daily life (Baum et al., 1996; Werner et al., 2009). In general, VR can be said to be a more cognitively challenging environment because there is a lot of information to be processed from the environment. Giovanetti et al. (2019) also compared the performance of the kitchen task in VR and the real environment.

The evaluation approach of observing task performance in VR through HMD has recently received a lot of attention and is emerging as a methodology that can increase the ecological validity of cognitive function evaluation (Parsons, 2014). However, it is necessary to have an in-depth understanding of the cognitive process of the VR environment and motor execution within it. Perceptions and behaviors in VR are fundamentally different from those in the real world. Real daily surroundings are very familiar to us because we always see and live among them. Therefore, it has been found that the real environment is not specially processed in one's life, or it is processed at the unconscious level. Meanwhile, since the graphics in VR are new and considered "fancy", it has been found that the amount of salient information increases from the point of view of information processing. Such VR with abundant sensory stimulation acts as a distracting factor in cognitive processing, especially among the elderly, and additional cognitive functions are required to suppress it to perform target behavior. (Allain et al., 2014; Parsons & Rizzo, 2008).

According to the results of this study, it was found that there is an effect on the kitchen task execution time according to the environment, task difficulty, and age group. There was no difference between the young adults and the elderly in performing tasks in the real environment (t=1.63, p=.637), but there was a difference between the two groups in VR (t=-9.23, p<.001). Because VR performance is more difficult, it can be said that this represents the difference between the two groups. Previous research results also show that the group with lower cognitive function shows a larger difference in performance in VR and reality (Cushman, Stein, & Duffy, 2008). According to the results of this study, the difference between VR and reality was larger in the elderly group than in the healthy adult group, and the lower the cognitive function among the elderly group, the greater the difference between performance in VR and reality. Allain et al. (2014) also compared dementia and healthy elderly people, and it was found that the dementia patient group took longer to perform in VR and showed more errors than the healthy elderly. The difference in execution time between the real environment and VR according to cognitive function suggests that there are more cognitive challenges in VR.

The interesting thing is that in the case of young adults, it took longer to perform the kitchen task in the real environment than in VR, and, conversely, it took longer for the elderly to perform the task in

VR. This pattern was the same for both easy and difficult tasks, regardless of the difficulty of the task. In the case of young adults, while the controller manipulation in VR was proficient, there is a possibility that the elderly performed poorly because it was difficult to manipulate objects in VR due to lack of hand dexterity. It was judged that the adaptation to the new interface is faster than that of the elderly group, even though they have never used HMD except for two of the participants in the young adult group.

Meanwhile, the difference in execution time in VR and reality was different depending on the difficulty of the task. There was an interaction effect between environment and task difficulty (F=9.58, p=.003). As a result of the post-test, it appears that there is no difference in execution time between VR and reality for easy tasks, and there is a difference between VR and reality for difficult tasks. When the task is easy, the cognitive capacity used to handle the task and adapt to manipulation in the virtual environment is sufficient, whereas in the virtual environment, the cognitive overload occurs when the task is difficult (Baddeley, 1992; Sweller, 1988). In other words, when the difficulty of the task and the difficulty of the environment are simultaneously high, it can be said that the actual performance is lowered due to cognitive overload.

In addition, this result supports the finding that it takes longer due to cognitive overload, rather than the assumption that it takes longer to perform because it is difficult to manipulate the environment and objects in VR. If it is simply difficult to manipulate an object, even if the task is easy, it should take longer to perform in VR than in reality. It means that one has demonstrated cognitive capacity.

In addition, this result showed that a different pattern emerges according to age. For young adults, there was no difference between VR and reality when the task was easy, and there was a difference between VR and reality when the task was difficult. Meanwhile, in the case of the elderly, there was a difference in the time required between VR and reality regardless of the difficulty of the task (E*TD*A). This shows that there is a difference in cognitive capacity even though the average mini-mental state exam (MMSE) score between the two groups of adults and the elderly participating in this study is the same. In other words, it was thought that cognitive resources were used more in the case of the elderly because they were not familiar with sensorimotor control in VR. In the case of the elderly, it was thought that more cognitive sources are used for cognitive adaptation to the VR environment than the real environment (Cushman & Duffy, 2008). Performing tasks in VR requires more cognitive load and represents inefficiency of movement.

In the case of a difficult task, young adults and the elderly move at a similar level in the real environment, but in VR, the movements of the young group are very simplified and the movements of the elderly increase. Young adults seem to have strategic skills for movement within VR. It was thought that although they only used HMD for the first time, they would have used the learned movement strategy in the VR of personal computers (PCs) and smartphones.

According to the Cognitive Load Theory (CLT), manipulating objects and performing tasks in unfamiliar virtual environments can induce cognitive overload. The movements we walk, reach, and grasp in real life are unconsciously controlled and are precognitive matter. However, bodily awareness in VR is totally changed and we need to adapt on new sensorimotor generating loops (Murray & Gordon, 2001). However, if one is basically accustomed to moving and manipulating within these environments, they will not experience cognitive overload in performing tasks (Sweller, 1988). In the case of young adults who frequently use computers and tablets, sensorimotor adaptation in VR is easier than among an elderly group; therefore, it is considered to be faster and more efficient in performing in VR than in the real environment.

In this study, although the cognitive level between the young adult group and the elderly group was the same, it was found that there was a difference in the time it took to perform a task in VR and the movement flow. Rather than simply saying that cognitive ability predicts the performance of VR, this suggests that it can be changed by sensorimotor adaptation to VR. As explained in Sweller’s CLT theory, it is the same as the argument that determining performance depends on the intrinsic load of the task itself and the extraneous load given in the performance environment. In this study as well, the use of cognitive cappers differed according to the difficulty of the task and the difficulty of the performance environment.

When developing an evaluation based on VR in the future, it is necessary to consider setting a task that appropriately challenges the cognitive load of the elderly. Rather, it is considered inappropriate to apply the difficulty of observation-based evaluation performed in the real environment to VR as it is. In future research, it will be necessary to confirm the claims of this study by comparing the performance of the elderly groups with different cognitive levels. In addition to cognitive function, it is thought that an experiment to rule out the difference between the two groups due to academic background is also necessary.

In conclusion, the cognitive load differences between VR and real environments were evaluated by comparing young adults and elderly groups and how they were affected by task difficulty. According to the results of this study, it is suggested that VR-based cognitive evaluation should be developed considering the cognitive overload of the elderly in VR environment in the future.

CHAPTER 4. The Efficiency of Movement Trajectory and Sequence in VR According to Cognitive Function in the Elderly

4.1 Introduction

In the process of aging, the reactivity of the nervous system also changes. Reaction time increases and the accuracy of sensory perception decreases with aging (Prince, Corriveau, Hébert, & Winter, 1997). Strategies are also employed to use the least amount of energy due to physical deterioration which is the so-called *minimal energy cost* (Clark, 1995). That is, it tends to predict the environment and control the movement that uses the body energy to the minimum. This is a way to adapt to declining physical systems as well as aging.

However, with cognitive aging, it is suggested that the ability to predict the environment is poor and there is difficulty in cognitive control regarding the strategy to minimize energy. According to previous research, older adults tend to scan for information from the surrounding environment more frequently than younger adults while they are walking or moving (Kirasic, 1991). This is a strategy to continuously seek information from the environment because the information processed in the nervous system is insufficient and vulnerable. To reduce the prediction error referred to in the predictive brain model, it is necessary to provide feedback of continuously updated information about the actions performed. Motor control is based on the process of minimizing prediction error online. For this reason, the pauses or inefficient movement occurs more often as the uncertainty about the information required for the movement increases. As the predictability of behavior decreases, such behavioral characteristics may appear and it is related to the cognitive function of the central executive (Baddeley, 1996).

In a previous study, when the distance traveled by the healthy elderly and the elderly with cognitive decline while performing a virtual task was compared, the total amount of movement was found to be similar (Josman et al., 2014; Werner et al., 2009; Zakzanis, Quintin, Graham, & Mraz, 2009). However, the elderly with cognitive impairment appeared to show inefficient movement compared to the healthy elderly (Cushman et al., 2008). In the previous results of the elderly with MCI, the pause time in the virtual shopping task was longer than that of the healthy elderly (Werner et al., 2009). In the virtual navigation task, as compared to the healthy elderly, the elderly with Alzheimer's dementia did not tend to explore the surrounding environment before starting to move. In addition, it was found that there were many errors of finding the wrong way or turning in the direction. As such, various behavioral characteristics appear according to cognitive functions in VR tasks.

In the previous literatures, the frequency of wrong turns or incorrect actions is sometimes used as an index (Werner et al., 2009; Zakzanis et al., 2009), and the duration of pause of movement was also analyzed as an index. (Josman et al., 2014). Evaluation of these behavioral characteristics can be suggested as a new ecological alternative to achieve more accurately screen early detection of cognitive aging.

As a process of aging well, the body tends to use the least amount of energy by minimizing the distance moved as the physical body aged (Kirasic et al., 1992). If cognitive function is not operated to plan and execute the movement, it can cause unnecessary body movements. Therefore, according to the cognitive function, the qualitative difference in sequence or trajectory of movement can be observed.

Before the onset of cognitive deterioration, cognitive decline appears priorly in the functioning of activities of daily living. Even in patients with dementia, it is known that they exhibit executive dysfunction in daily life before being diagnosed (Giebel et al., 2015; Voss & Bullock, 2004). As a type of executive dysfunction, it appears as an error in the performance of a daily task or in inefficient movement. In particular, omission and object substitution errors are frequently seen in dementia patients (Giovannetti et al., 2002). While inefficient movement can be recognized intuitively by observing the performance in the real environment, it is difficult to provide an accurate definition of inefficient movement. In this respect, it is a great advantage to be able to perform tasks in VR, digitalize and record the trajectory of movement, and analyze them quantitatively. Interpreting this quantified movement information helps to identify behavioral characteristics caused by cognitive aging.

This study aimed to explore the possibility of observing cognitive declines through movement sequence inefficiency and movement trajectory features.

4.2 Methods

(1) Participants

A healthy young adult group (*n*=24), an elderly group (*n*=38), and an MCI group (*n*=4) participated in this study. The mean age of younger adults was 24.1 (SD ±4.26; 18 females and 6 males). The mean age of healthy elderly was 67.6 (SD ±5.62; 31 females and 7 males) and MCI was 66.0 (SD ±5.19; 2 females and 1 males). They all were novice for HMD devices.

(2) Task Description of Making Coffee

The coffee making task is divided into a total of 6 sub-step tasks. The task starts in the front of the sink (AOI 1), gets the cup from the cupboard above the sink, then moves to AOI2 to pour coffee from the coffee machine and put the sugar in it. When the coffee is ready, it is asked to serve on the table in the AOI3 and then the task is finished. After restoring and cleaning the stuff to be organized, return to the AOI1 area and finish the task.

(3) Definition of Area of Interest (AOI)

Three areas of interest (AOI) were defined in the virtual reality kitchen space. These 3 AOIs are areas that must be visited to perform the coffee-making task. In the coffee making task, all subjects start at AOI1, take out a cup from the shelf in AOI1, and move to AOI2. AOI2 is an area where stuffs being necessary to make coffee were placed such as a coffee machine, sugar, and spoon. AOI3 is a place that serves ready-made coffee. When the task is finished, the participant must return to AOI1 to finish the task, and additional movement may occur between AOI1 and AOI2 to clean up used tableware.

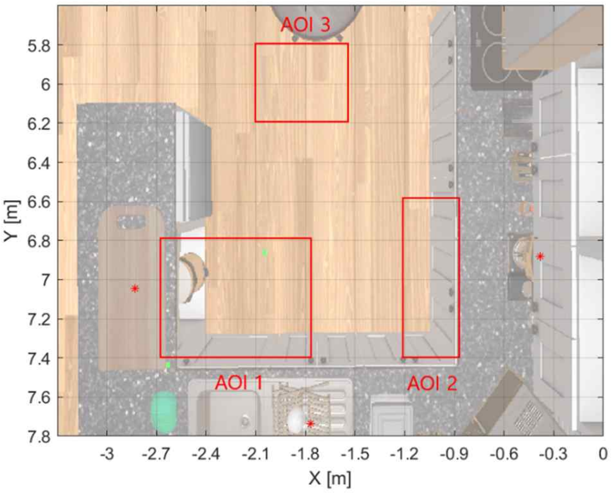


Figure 7 Definition of area of interest (AOI) on the virtual coordinate

4.3 Results

(1) Movement Trajectory

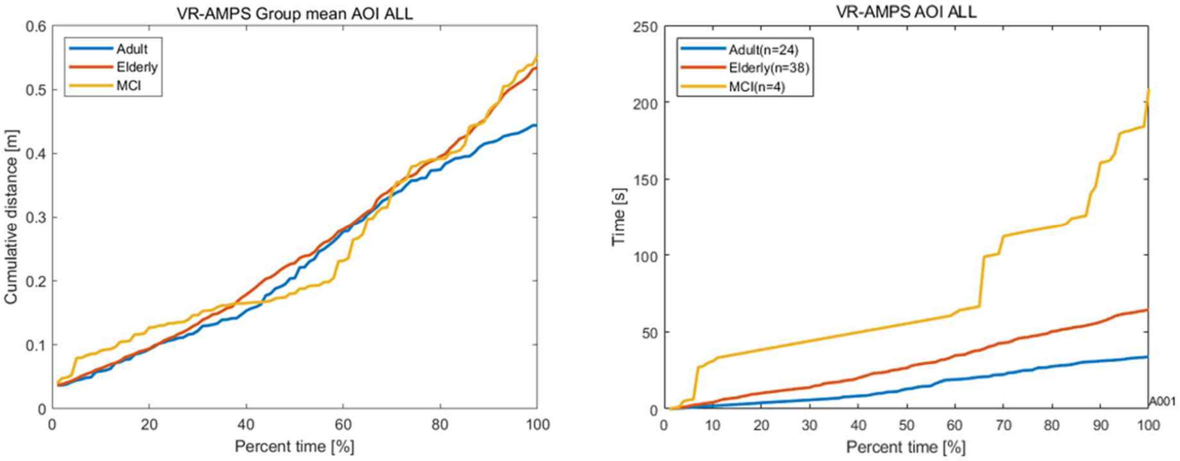


Figure 8. Total distance travelled(left) and total time(right) to performance virtual coffee task among young adults, the elderly, MCI group

While performing the virtual coffee task, the distance travelled and the time between the three groups were plotted according to the progress (%) of time. As a result, in the case of normal adults, the total distance travelled was the shortest compared to the healthy elderly and the elderly with mild cognitive impairment (MCI). In the healthy elderly and the MCI elderly, the total amount of distance travelled was similar, but it was observed that the profile of the distance travelled was different. In other words, it was found that the MCI elderly moved less distance than the normal elderly until the middle part of the task, but moved more toward the latter part of the task. There was a difference between the three groups in the time required to perform the task, and it was found that the MCI elderly group took the longest to perform the task. In the case of the elderly with MCI, the profile of the time it takes to perform a task was different from that of the other two groups.

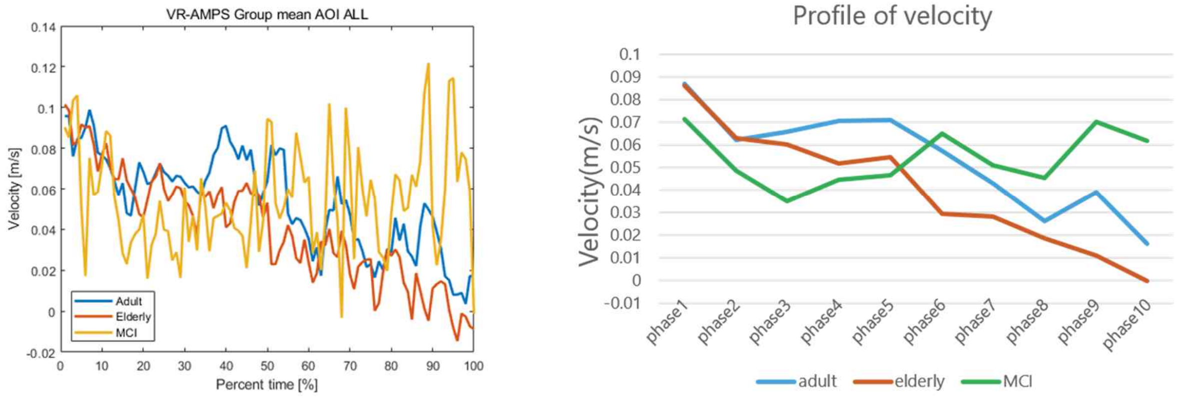


Figure 9. Velocity and profile of velocity of movement while performing the task among young adults, the elderly, MCI group

Velocity while performing the task was plotted. In healthy elderly and young adults, the movement speed was stably slowed as the task progresses till finishing the task, but in the MCI, the movement speed increased or decreased during task performance.

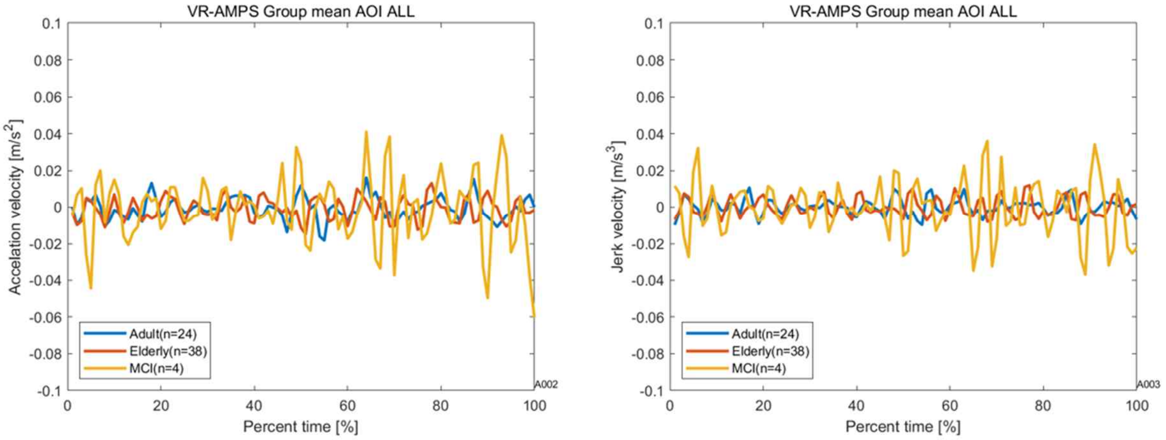


Figure 10. Acceleration and jerk while performing the task among young adults, the elderly, MCI group

It is the result of analyzing the acceleration and jerk of movement by differentiating the moving speed with time. As a result, in the case of the elderly with MCI, variability in motion acceleration and jerk movement were observed prominently throughout the task.

(2) Sequence of Movement

Table 5. Average number of visits between AOIs in young and older adults with high cognitive function and low cognitive function

Groups	Average number of visits
Young adults (*n*=24)	5.65 (SD 0.98)
The elderly with high cognitive function (*n*=35)	6.32 (SD 1.53)
The elderly with low cognitive function (*n*=7)	8.40 (SD 2.37)

* criteria for low cognitive function < MMSE26

In the young adults, the number of transfers between AOIs when performing the coffee-making task was about 5.65 (SD 0.98), whereas the number of transfers between AOIs was 6.32 (SD 1.53) for healthy elderly people. On the other hand, the elderly with mild cognitive function showed an 8.40

(SD2.37) visits between AOIs while performing the same task.

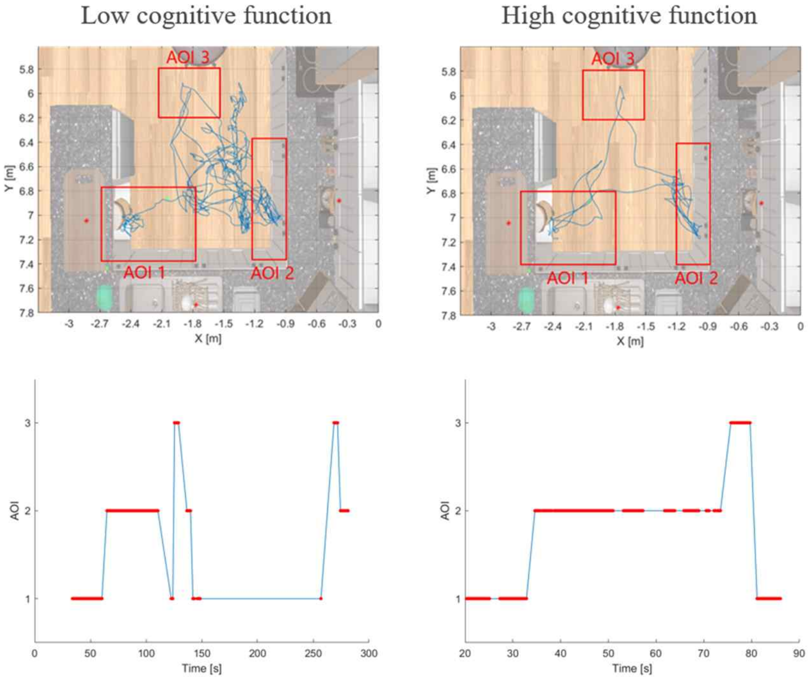


Figure 11. Sample individual data of path between AOIs while performing the task in VR in the elderly with low cognitive function and high cognitive function

4.4 Discussion

As we age, it causes the nervous system to become less responsive and slows down the process. In response to physical deterioration, the elderly adopts strategies to minimize physical movement (*minimal energy cost*) (Clark, 1995). To minimize movement, it is necessary to make a planned movement after sufficiently exploring the information about the environment in which the action is to be taken. According to the results of previous research, it has been reported that the less planned the movement is, the busier the movement and the more frequent errors in the performance. Such characteristics can be suggested as observable indicators of cognitive decline.

In addition, the definition of unplanned and inefficient movements when performing the task is unclear in the real environment, so the criteria of decision-making depend on the intuition of experts. In this respect, saving the trajectory of the movement on the coordinates during the performance of the task in VR has the advantage of quantitatively analyzing the characteristics of movement. In this study, the analysis was conducted focusing on the pattern of movement trajectory and inefficiency of sequence.

The distance traveled and time spent by groups of healthy adults, the healthy elderly, and mild cognitive impairment (MCI) elderly were compared during the coffee-making task. As a result, it was found that the elderly traveled more distance than the young adults, but there was no difference in the total amount of distance traveled by the healthy elderly and the MCI group. In terms of time spent, there was little difference in the time spent by healthy adults and the healthy elderly, but the time spent by the elderly with MCI was much longer, and in particular, it showed a non-linear increase of time.

As a result of analyzing the movement speed, acceleration, and jerk with the distance and time, the pattern of acceleration and jerk of movement was more prominent in the MCI elderly compared to the other two groups. This suggests that abrupt and jerk movements appear in performing the task in the elderly with cognitive decline. Fluent movement is very sophisticated in movement control and can be seen to be regulated by higher cognitive functions. When the prediction of behavior toward the environment is lowered, unplanned and rushing behaviors can appear.

The sequence moved to perform the coffee-making task was analyzed. As a result, it was found that there were more sequences in the elderly than in young adults. Additionally, within the elderly group, there were more stages of movement in the low cognitive function group than in the high cognitive function group. According to age and cognitive function, there appeared to be inefficiency of sequence of movement. In this regard, behavioral sequence problems have been found to be closely related to memory function (Baddeley, Wilson, and Kopelman, 2002). It can also be considered as a typical executive deficit. Executive function is considered a cognitive function that performs a series of steps to achieve a goal, and it is required to connect and coordinate the sub-steps. If such a function does not work properly, a problem in the sequence will appear on task performance. Clinically, it is diagnosed as dysexecutive function or apraxia (Fjell, et al., 2017; Petreska et al., 2007).

The kinematic analysis and the efficiency of sequence of such movements show the potential to be used as an indicator for observing cognitive decline on actual task performance. In a future study, it is recommended that it will be useful to learn movement trajectory patterns using machine learning technique as an artificial intelligence methodology to distinguish the movement patterns of the elderly with cognitive impairment and those without it.

CHAPTER 5. Factors that Affect the Performance of Virtual Kitchen Tasks in the Elderly

5.1 Introduction

The implementation of virtual reality (VR) using head mounted display (HMD) and the development of metaverse-based content is being actively carried out. Interest in the application of content using VR for rehabilitation is also increasing (Clay et al., 2020; Riva, Castelnuovo, & Mantovani, 2006; Schultheis & Rizzo, 2001). The evaluation based on VR encourages the interest of the patient by constructing diverse and lively environments, thereby encouraging them to participate in rehabilitation. Additionally, it can be considered cost-effective in constructing an evaluation environment and context. However, the biggest obstacle to using VR as a therapeutic medium is that most patients are elderly. In the case of young adults, even when they are exposed to HMD for the first time, they quickly re-adapt their perception and sensory-motor control to suit VR. Hence, unlike the elderly, they are proficient in manipulation and performance in VR (Plechatá et al., 2019).

According to previous studies on VR, the most of older adults spent more time on completing VR tasks and showed more errors in performing such tasks than younger adults (Plechatá et al., 2019; Zakzanis et al., 2009). An abundance of sensory information is required to be processed in VR. Hence, there might be a cognitive overload when processing the sense of presence (Plechatá et al., 2019; Richards & Taylor, 2015). With age, cognitive capacity tends to decrease, and the ability to inhibit unnecessary information decreases (Salthouse & Meinz, 1995). A decrease in cognitive capacity of the elderly leads to poorer performance of VR tasks. Furthermore, it is also known that the decline in performance in VR is greater than that in the real environment when there is cognitive deterioration (Cushman et al., 2008). Thus, VR is considered to provide greater cognitive challenges than the real environment.

An evaluation context that can provide a greater cognitive challenge is ecologically valid for neuropsychological tests. In general, traditional neuropsychological assessment is based on the pencil and paper test and consists of simple tasks that reflect cognitive conceptual constructs. Therefore, there are discrepancies between the results of neuropsychological tests and the functioning of daily life (Chaytor & Schmitter-Edgecombe, 2003; Shallice & Burgess, 1991). Even in the case of the Mini Mental State Examination (MMSE), a ceiling effect appears in the group with high educational attainment. Additionally, even if a person has borderline cognitive impairment in carrying out daily functions, they often obtain high scores on neuro-psychological tests, or vice versa (Bryant et al., 2008; Hoops & Stern, 2009). Since the human brain is likely to compensate for the lesion, functional impairment may appear slower than the pathological changes in the brain (Meng & D'Arcy, 2012; Stern, 2013). In other words, it depends on an individual's cognitive reserve capacity, and it is known that individuals with higher education or intelligence tend to use a strategy to compensate for this cognitive deterioration (Meng & D'Arcy, 2012). Therefore, there has been a growing interest in how to sensitively evaluate brain function before its deterioration becomes severe (Chaytor & Schmitter-Edgecombe, 2003).

Recently, ecological feasibility studies of neuropsychological evaluations have focused on how well the results of the evaluation are related to everyday functioning (veridicality) and whether tasks are simulating cognitive skills well in everyday life (verisimilitude) (Chaytor & Schmitter-Edgecombe, 2003; Parsons, 2014). Performance-based VR evaluation can be considered as an approach with good veridicality and verisimilitude (Fernandez Montenegro & Argyriou, 2017). VR can create computer-generated simulations which are similar to the real world, and the virtual environment using HMD makes it possible to react naturally within it.

Among the various domains of cognitive function, executive function is attracting attention to identify early dementia. In patients with frontal lobe dementia or mild cognitive impairment (MCI), the problem of executive function is closely related to dysfunction in activities of daily living (ADL). Executive functions are complex and high-level cognitive functions. It is difficult to define a converging concept, and it is more likely to define a set's ability to achieve goal-directed behavior through the processes of planning, sequencing, monitoring, and correction (Barkley, 2012). To evaluate executive functions, task-oriented assessments such as kitchen, shopping, and errand tasks are typically used (Allain et al., 2014; Giovannetti et al., 2019; Ouellet et al., 2018; Parra & Kaplan, 2019). All these tasks have a common requirement of the need for completing a series of sub-steps to achieve the final goal.

The types of instructions for kitchen tasks in the paradigms in the aforementioned literature were as follows: bringing out a set of ingredients after looking at a list, packing a lunch, and setting the table considering the time each food is cooked (Bialystok, Craik, & Stefurak, 2008; P Gamito et al., 2015; Giovannetti et al., 2019). Accuracy and efficiency are important for completing tasks. However, despite the accuracy of task performance being near-normal or normal, the efficiency in the process of performance wanes as the elderly become older, due to problems that develop in executive function (K. C. Kirasic, 1991). According to the results of previous studies, the inefficiency of time and movement was shown during the kitchen task in the elderly who were healthy as well as those who were suffering from dementia (Allain et al., 2014; Pedro Gamito et al., 2020). Furthermore, although there is no difference in achievement, micro-errors are still frequently observed in the aged group (Rycroft, Giovannetti, Divers, & Hulswit, 2018). These results suggest that the problem of efficiency of performing a task, rather than the problem of accuracy of a task, is a prominent feature in the early stages of cognitive aging.

Cognitive aging can be identified by performing tasks in VR. However, the individual variance in the elderly group is large in VR performance. In the elderly, there is a difference between those who are very good at VR tasks and those who are not good at it. It is conceivable that the individual characteristics of the elderly affect their adaptation to VR. Particularly, it is known that cognitive function and functional level of ADL are significantly correlated with VR (Parra & Kaplan, 2019; Zakzanis et al., 2009). Additionally, demographic characteristics such as gender, education, occupational history, and experience of using smartphones or computers are expected to be related to the quality of performance in the virtual task (Felnhofer, Kothgassner, Beutl, Hlavacs, & Kryspin-exner, 2012; Plechatá et al., 2019).

In general, neuropsychological tests interpret results by considering demographic factors(LaRue, 1992; Ross & Lichtenberg, 1997). The results were commonly adjusted according to age and educational level. In people with brain damage, neuropsychological functioning is known to have a significant relationship with age and education (Ross & Lichtenberg, 1997). Before using the VR task for evaluation approach, it is necessary to study the effect of the VR environment itself according to the demographic variables of elderly subjects(Mcgeorge et al., 2001).

The purpose of this study is to investigate the effects of age, education level, and general cognitive function on the elderly in their performance of virtual kitchen tasks.

5.2 Materials and Methods

(1) Participants

Forty-two older adults (age > 60 years) participated in this study. Participation in the study was not limited by the level of cognitive function, and the elderly with various levels of cognitive functions were recruited. They were not diagnosed with dementia or neurological diseases. The following persons were excluded from the study: (a) people who could not walk independently, (b) people who had visual or auditory deficits, and (c) people who had used HMD before. An informed consent form was provided to all participants, and they were paid monetary rewards.

(2) Experimental setting

The experimental setup was established in a 4*5M indoor room to enable free movement while wearing the HMD (Figure 1). Both natural and reflected lights were restricted and were free from noise. There were no obstacles to walking in the room. The HMD was HTC VIVE Pro Eye and VR display of 1440*1600 pixels and a refresh rate of 90 Hz. The visual field was a maximum of 110° at a glance and 360° surroundings could be viewed if the participant turned their head. Virtual kitchen furniture and kitchenware were created with high-quality graphics to enhance the sense of immersion.

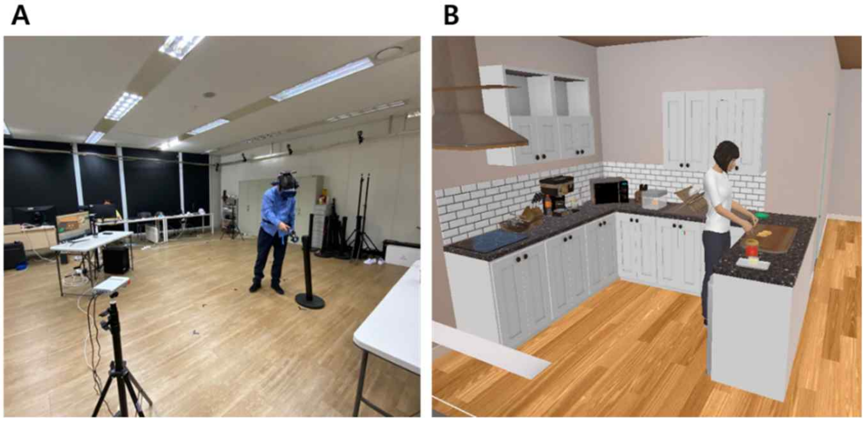


Figure 12. (A) Experimental setting, (B) virtual kitchen scene

(3) Virtual kitchen tasks

The virtual kitchen tasks were of two types: making butter and jam sandwiches and preparing coffee. The butter and jam sandwich task required participants to make a sandwich with two slices of bread which had to be spread with both jam and butter and then cut the sandwich in half. Next, they were asked to serve the sandwich on a plate and bring it to the table. The coffee preparation task required participants to pour coffee that had already been brewed in a coffee machine into a cup and then add sugar to it. Next, they were asked to bring the coffee to the table.

(4) Procedure

The order in which tasks were to be performed by each participant was randomized, and each participant performed both tasks. For participants to fully adapt to VR before performing the task, the location of the objects was noted, and movements such as grasping, releasing, cutting, opening, closing, carrying, and swiping were practiced using the controller. All participants practiced the tasks once with verbal cues and then participated in the experiment. All tasks started in front of the sink, with the participants facing it, and when the tasks were completed, they returned to the same place.

(5) Data analysis

Data were analyzed using Statistical Package for the Social Sciences (SPSS) 27.0. The variables were analyzed using descriptive statistics. Pearson correlation analysis was used to determine the correlation between variables. Multiple regression analysis was used to examine the effect of each independent variable on the dependent variable.

5.3 Results

(1) Descriptive statistics

Descriptive statistical analysis was performed to determine participants' characteristics and the results are shown in Table 6. The average age of the participants was 67.76 and their ages ranged from 60 to 79 years. The mean MMSE score of the participant group was 27.4, the minimum was 21, and the maximum was 30. The average years of education were 8.86 (SD ± 3.447). The level of education ranged from no education to graduation from graduate school.

The average distance (m) traveled to make a sandwich in VR was 50.87 (SD ± 21.267), and the average distance (m) traveled to prepare coffee was 18 (SD ± 7.396). The average time (s) for making a sandwich in VR was 338.67 (SD ± 132.521), and the average time (s) for preparing coffee was 128.83 (SD ± 61.93). For the normality test, both univariate and multivariate normality were reviewed, and skewness and kurtosis were identified among the normality items. As a result, it was found that skewness and kurtosis do not exist in the assumption of univariate normality.

Table 6. Descriptive statistics of variables (*n*=42)

	Minimum	Maximum	Mean	SD	Variance	Skewness	Kurtosis
MMSE	21	30	27.4	2.45	6	-1.028	0.58
Education	0	18	8.86	3.447	11.9	0.322	0.498
Age	60	79	67.76	5.759	33.2	0.14	-1.039
TD_VRsandwich	29	136	50.87	21.267	452	1.985	5.155
TD_VRcoffee	9	36	18	7.396	54.7	1.231	0.809
TT_VRsandwich	148	855	338.67	132.521	17562	1.807	4.592
TT_VRcoffee	57	336	128.83	61.93	3835	1.405	1.865

TD, total distance; TT, total time; SD, standard deviation.

(2) Correlations between age, education, general cognitive function, and VR performance

Table 7. The results of correlation analysis between independent and dependent variables

	MMSE	Education	Age	TD_VR sandwich	TD_VR coffee	TT_VR sandwich	TT_VR coffee
MMSE	1						
Education	.625**	1					
Age	-0.154	-0.045	1				
TD_VRsandwich	-.419**	-0.198	0.214	1			
TD_VRcoffee	-.469**	-0.281	-0.086	.404**	1		
TT_VRsandwich	-.529**	-0.293	0.197	.922**	.458**	1	
TT_VRcoffee	-.502**	-.339*	-0.065	0.243	.875**	.418**	1

TD, Total Distance; TT, Total Time; *p<0.05, **p<0.01

Pearson's correlation analysis was performed to determine the correlation be-tween each variable and it is shown in Table 7. MMSE scores showed a significant negative correlation with TD_VRsandwich (r= -.419, p<.01), TD_VRcoffee (r= -.469, p<.01), TT_VRsandwich (r= -.529 , p<.01), and TT_VRcoffee (r= -.502, p<.01). Education showed a significant negative correlation only with TT_VRcoffee (r= -.339, p<.05). In contrast, TD_VRsandwich, TD_VRcoffee, and TT_VRsandwich did not show a significant correlation with education. With respect to age, TD_VRsandwich, TD_Vrcoffee, TT_Vrsandwich, and TT_Vrcoffee showed no significant correlation.

(3) Influence of age, education, and general cognitive function on total distance traveled to make a sandwich in VR

Table 8. Multiple regression model for distance traveled in VR sandwich task

	Total Distance(TD)_VRsandwich									
	B	*SE*	*β*	*t*	*p*	VIF	DW	R^2	$_{adj}R^2$	F (*p* value)
(Constant)	116.777	58.063		2.011	.051					
MMSE	-3.946	1.631	-.455	-2.419	.020*	1.685	2.440	.204	.141	3.244*
Education	.575	1.147	.093	.501	.619	1.648				(.032)
Age	.548	.542	.148	1.011	.319	1.029				

Multiple regression analysis was performed to determine whether MMSE, education and age affect the distance traveled while performing the virtual sandwich task. The regression model was found to be statistically significant (F=3.244, p=.032), and the explanatory power (R2) of the regression model was 20.4%, which is moderate. The adjusted R2 value was 14.1% (Table 8). Since the variation inflation factor (VIF) was less than 10, there was no problem of multicollinearity. The Durbin–Watson statistic was 2.44, which is close to 2, so there was no autocorrelation, and the independence of the residuals was satisfied.

First, in terms of MMSE, the non-standardized beta was -3.946, and it was found to have a statistically significant negative effect (t=-2.419, p=.020). That is, when the MMSE score increased by 1 point, TD_VRsandwich decreased by 3.946m. However, education and age did not appear to have a statistically significant effect.

(4) Influence of age, education, and general cognitive function on total distance moved to prepare coffee in VR

Table 9. Multiple regression model for distance traveled in VR coffee task

	Total Distance(TD)_VRcoffee									
	B	SE	Beta	t	p	VIF	DW	R^2	${}_{\text{adj}}R^2$	F
(Constant)	74.223	19.648		3.778	0.001					
MMSE	-1.557	0.552	-0.516	-2.821	.008**	1.685	1.53	0.246	.187	4.139*
Education	0.074	0.388	0.034	0.19	0.851	1.648				(.012)
Age	-0.21	0.183	-0.163	-1.143	0.26	1.029				

Multiple regression analysis was performed to determine whether MMSE, education, and age affect the distance moved while performing the virtual coffee task. The regression model was found to be statistically significant (F=4.139, p=.012), and the explanatory power (R2) of the regression model was 24.6%, which is moderate explanatory. The adjusted R2 value was 18.7% (Table 9). Since the VIF was less than 10, there was no problem of multicollinearity. The Durbin–Watson statistic was 1.53, which is close to 2, so there was no autocorrelation, and the independence of the residuals was satisfied.

First, in terms of MMSE, the non-standardized beta was -1.557, which was found to have a statistically significant negative effect (t=-2.821, p=.008). That is, when the MMSE score increased by 1 point, TD_VRcoffee decreased by 1.557(m). However, education and age did not appear to have a statistically significant effect.

(5) Influence of age, education, and general cognitive function on total time spent to make a sandwich in VR

Table 10. Multiple regression model for time spent in VR sandwich task

	Total time(TT)_VR sandwich task									
	B	SE	Beta	t	p	VIF	DW	R^2	$_{adj}R^2$	F
(Constant)	945.771	340.55		2.777	0.008					
MMSE	-29.356	9.565	-0.543	-3.069	.004**	1.685	2.415	.295	.239	5.293** (.004)
Education	1.958	6.725	0.051	0.291	0.773	1.648				
Age	2.657	3.18	0.115	0.836	0.409	1.029				

Multiple regression analysis was performed to determine whether MMSE, education, and age affect the time spent performing the virtual sandwich task. The regression model was found to be statistically significant (F=5.293, p=.004), and the explanatory power (R2) of the regression model was 29.5%, which can be said to have moderate explanatory power. The adjusted R2 was 23.9% (Table 10). Since the VIF was less than 10, there was no problem of multicollinearity. The Durbin–Watson statistic was 2.415, which is close to 2, so there was no autocorrelation, and the independence of the residuals was satisfied.

First, in terms of MMSE, the non-standardized beta was -29.356, and it was found to have a statistically significant negative effect (t=-3.069, p=.004). That is, when the MMSE score increased by 1 point, TT_VRsandwich decreased by 29.356(s). However, education and age did not appear to have a statistically significant effect.

5.3.6 Influence of age, education, and general cognitive function on total time spent to prepare coffee in VR

Table 11. Multiple regression model for time spent in VR coffee task

	Total time(TT)_VR coffee task									
	B	SE	Beta	t	p	VIF	DW	R^2	$_{\text{adj}}R^2$	F
(Constant)	588.289	161.591		3.641	0.001					
MMSE	-12.761	4.539	-0.505	-2.812	.008**	1.685	1.613	.273	.215	4.753**
Education	-0.543	3.191	-0.03	-0.17	0.866	1.648				(.007)
Age	-1.548	1.509	-0.144	-1.026	0.311	1.029				

Multiple regression analysis was performed to determine whether MMSE, education, and age affect the time spent performing the virtual coffee task. The regression model was found to be statistically significant (F=4.753, p=.007), and the explanatory power (R2) of the regression model was 27.3%, which can be said to have moderate explanatory power. The adjusted R2 was 21.5% (Table 11). Since the VIF was less than 10, there was no problem of multicollinearity. The Durbin–Watson statistic was 1.613, which is close to 2, so there was no autocorrelation, and the independence of the residuals was satisfied.

First, in terms of MMSE, the non-standardized beta was -12.761, and it was found to have a statistically significant negative effect (t=-2.812, p=.008). That is, when the MMSE score increased by 1 point, TT_VRcoffee decreased by 12.761(s). However, education and age did not appear to have a statistically significant effect.

5.4 Discussion

In addition to the recently developed VR implementation technology, VR is attracting attention as a method of evaluating and treating patients with cognitive disabilities. Considering that most of the participants were elderly, it is necessary to investigate the acceptability and characteristics of VR performance in the elderly group. The purpose of this study was to investigate the effects of age, cognitive level, and educational background on the elderly population in their performance of the virtual kitchen tasks.

It is known that age affects negative attitudes toward VR using HMDs (Huygelier et al., 2019). Furthermore, it is expected to be difficult to perform VR tasks because of cognitive aging and unfamiliarity with devices (Plechatá et al., 2019; Salthouse & Meinz, 1995). According to the results of previous research on VR tasks, the level of performance differs according to age (Carelli et al., 2011). However, even within the elderly group, the level of performance appears to be heterogeneous. It is expected that the various individual demographic factors of the elderly affect the VR task performance.

As a result, we found that there was no correlation between age and VR performance in the elderly. Particularly, it was found that age did not affect the time taken and distance traveled during both the sandwich making and coffee preparation task, which had different difficulty levels. Although it is known that younger adults out-performed older adults in VR tasks (Carelli et al., 2011; Parra & Kaplan, 2019; Zakzanis et al., 2009), there was no difference in time taken for performance and distance traveled according to age within the elderly group. Contrarily, Oliveira's study concluded that age had a major effect on the quality of VR task performance by elderly persons ranging from 60 to 85 years in age (Oliveira et al., 2018). The most significant difference between Oliveira’s and our study is the type of VR platform and user interface devices that were used in the VR tasks. Age-dependent PC manipulation proficiency was thought to be affected by age in the Oliveira’s 2D virtual task.

In fact, two factors influence the performance of VR tasks: the first is the cognitive capacity to process the sense of presence in VR, and the second is the sensorimotor control ability to interact with objects in VR(Allain et al., 2014; Plechatá et al., 2019). In case of 3D immersive VR, it is cognitively overloaded to process high-quality visual stimuli and present the sense of presence (Plechatá et al., 2019), but it is easier to perform in terms of sensorimotor control than 2D non-immersive VR. Natural ambulation was possible and it was also able to easily reach and grasp using a hand controller in 3D immersive VR in this study. It is concluded that the immersive platform and controlling device had little impact on the elderly according to their age.

The difference between the controlling methods of immersive and non-immersive VR is also influenced by education level (Zhang, Grenhart, McLaughlin, & Allaire, 2017). While non-immersive VR has a large effect on computer skill proficiency, including mouse manipulation such as drag and double clicking, an immersive VR environment will have a minimal effect. In this study, it was found that there was no correlation between the time spent in performing the sandwich task and education level. Additionally, there was no correlation between the distance traveled in the sandwich task and educational level. Contrastingly, it was found that the time spent performing the coffee task had a statistically significant correlation with education levels. However, the regression analysis showed that education level had no causal effect on the time taken to perform the VR coffee task. The kitchen task paradigm used in this study is frequently performed in daily life. Generally, assessments based on tasks of daily living are less influenced by education level than traditional neuropsychological assessments (Oliveira et al., 2018; Werner et al., 2009).

In the elderly, factors other than age and education have an impact on VR performance. The results of this study showed that the MMSE score was significantly correlated with the total time and distance required to perform both the sandwich and coffee tasks. General cognitive function can be the most influential factor in VR performance. Many studies have shown that patients with cognitive decline take longer to perform in VR and show performance errors more frequently (Cushman et al., 2008; Pedro Gamito et al., 2020; Giovannetti et al., 2019; Zakzanis et al., 2009). Consistent with results from previous studies, this study showed that the total time taken and distance traveled in the virtual kitchen task were significantly influenced by cognitive function.

In the study by Allain et al. (2014), patients with Alzheimer's dementia took long-er to perform the virtual coffee task, had a lower success rate, and had frequent behavioral issues compared to the healthy elderly. Additionally, it was also found that the difference between the healthy elderly and the AD in performing a task was vaster in VR than when the same task was performed in the real world. This is because VR provides conditions that give more cognitive challenges, even though it is done using a strategy that could be used to functionally compensate in daily life in the real world. VR can be considered to play role as a cognitive treadmill that tests the limit of cognitive capacity by adding the load of processing the VR environment in addition to the cognitive load required originally to perform the given task. For this reason, VR can be considered as a useful alternative for sensitive screening of cognitive decline in MCI or early dementia (Allain et al., 2014; Cushman et al., 2008; Okahashi et al., 2013).

Various types of VR tasks have been recognized as assessments for differentiating between various cognitive impairments (Werner et al., 2009; Zakzanis et al., 2009). The virtual supermarket task in Werner et al. (2009) required participants to bring shopping items, and the MCI showed a longer trajectory in a longer period for shopping in VR. Similarly, in a navigation task, dementia patients showed different abnormal movement characteristics from normal adults in finding a path and there was also a difference in the time and distance traveled overall (Zakzanis et al., 2009). Among various types of VR tasks, the kitchen task paradigm that we adopted is a representative behavioral evaluation used to screen for cognitive deterioration in patients (Baum et al., 1996; Rycroft et al., 2018). It was found that the time and distance required to perform the kitchen task at difficult difficulty showed larger variance than easy one, especially within the elderly group. It means that it is necessary to adjust the difficulty of the task in order to use the VR task as a cognitive evaluation with valid discrimination power.

In addition, the characteristics of kitchen tasks that perform a series of steps reflect executive functions (Alice & Giglioli, 2021; P Gamito et al., 2015; Giovannetti et al., 2019). Recently, it has been emphasized that executive function deteriorates in the early stages of dementia (Knopman et al., 2001; Voss & Bullock, 2004). It is thought that the index of the performance of the virtual kitchen task will be very useful in evaluating the executive function of dementia patients and in identifying problems caused by the dorsolateral prefrontal cortex (Voss & Bullock, 2004) . The VR easily creates a virtual task and systematically manipulate the environments, it also helps to study volition to move and interactions with paraphernalia in virtual environments for dementia (Garcia et al., 2012; Riva, Waterworth, & Waterworth, 2004).

Firstly, the limitation of this study is that it focused on the elderly group and did not scrutinize all age ranges. Secondly, there was no quasi-random allocation, and the subjects were randomly recruited. This resulted in fewer highly educated participants and failed to allocate the same number of participants in each class.

Nevertheless, it is concluded that this study showed the clinical utility of a sensitive and ecologically valid approach to evaluate cognitive decline in the elderly by implementing virtual kitchen tasks. It was found that the cognitive function of the elderly had the most important influence on their performance of the VR tasks rather than age and education. Despite prejudice against VR-based evaluation on the ground that it is difficult to apply to older people with less education, VR-based evaluation is a suitable method to evaluate pure cognitive function. Therefore, further research on persons suffering from various cognitive impairments such as MCI, dementia, brain injury, and stroke, should be conducted.

CHAPTER 6. Effect of Predictability of Sensorimotor Feedback on Cognitive Load in VR

6.1 Introduction

With the development of immersive VR implementation technology using HMD, research on cognitive function appearing in various types of virtual tasks has been actively conducted. In general, performing a task in the virtual environment appears to be more difficult than in the real environment. According to previous research, it appears that execution time and accuracy while performing a task in VR were different from the real environment (Cushman et al., 2008; Makransky et al., 2019). The reason for the different results of task performance between the VR and the real environment can be explained by two hypotheses. The first is because of the richness of information in the VR environment itself, such that the sense of presence requires more cognitive load on the processing. The second is that sensorimotor control in VR is difficult (Plechatá et al., 2019). Although ambulation and manipulation of objects in VR using HMD are natural and resemble real motion compared to 2D, the load of sensorimotor control occurs according to the fidelity of sensory feedback in VR (Huang, Luo, Yang, Lu, & Chen, 2020; Witmer & Singer, 1998).

According to the internal model theory, during sensorimotor control, an internal representation of the movement is created and elaborated by receiving continuous online feedback on the actual movement (Wolpert et al., 1995). The movement is more precisely controlled by correcting errors by comparing actual state with the prediction of the originally planned movement (Frith & Done, 1989). Sensorimotor control produces accurate motor movements mainly through the feedback of multisensory integration of the visual, tactile, and proprioceptive senses. In general, motor execution has been automated in a familiar mode that works when interacting with objects in the real environment (Kannape & Blanke, 2013; Wolpert et al., 1995).

However, visual feedback in VR is different from how it works in the real world. The degree of attribute of action varies according to the fidelity of the feedback on one's actions, and this determines the degree of immersion (Cooper et al., 2018). The characteristics of motor control vary according to the fidelity of visual feedback in VR. In addition, there may be more cognitive load acting on error correction according to the difference between visual feedback in VR and proprioception feedback of an actual moving hand (Cooper, 2010; Saunders & Knill, 2004). Most of the motor movements performed in daily life in real environments are automated and can be performed without conscious cognitive effort. However, conscious control is required for regulating the action when the performed action is unfamiliar (for instance, being a novice at driving).

One of the important factors to determine the cognitive effort to adapt sensorimotor control is the degree of perturbation of sensory feedback on one's movements. One's sensorimotor system will need to activate conscious motor control according to the degree of perturbation, thus consuming cognitive resources (Cooper, 2010). In the existing literature, sensory feedback is influenced by both the spatial and temporal properties of perturbation (Farrer, Bouchereau, Jeannerod, & Franck, 2008; Foulkes & Miall, 2000a; Van Den Dobbelsteen, Brenner, & Smeets, 2003). As the degree of perturbation increases, it becomes more necessary to recalibrate the attribution of one's action (Farrer et al., 2008). According to the results of previous studies, it was found that even if the angle of spatial perturbation varied from 0 to 13 degrees, no deviations were felt on a conscious level. The sense of immersion is affected even by a tiny degree of angular deviation, but the information of temporal delay does not appear to affect the attribution of action even if a very long delay is given (Farrer et al., 2008). Also, from the perspective of the neuronal mechanism, as the variability and uncertainty of sensory feedback increase, the cognitive load is also affected (Van Beers et al., 2002). The uncertainty of sensory feedback acts as noise in the internal loop of sensorimotor control system (Bays & Wolpert, 2007).

Taylor, Krakauer, and Ivry (2014) suggested the contribution of two different methods of processing sensorimotor adaptation, which are divided into implicit and explicit processing. If sensorimotor control works as the way to reduce the error between the generated command and sensory feedback in the forward model, implicit processing is based on the error calculation between the predicted aim of the motion command and the sensory feedback, and explicit processing is based on the error between the target and feedback of current position. Cognitive strategy through the interplay of two processes would decide and improve the quality of motor performance. While it is expected that there can be a strategy on how to reduce the error in two different processing, it is not known whether the uncertainty of sensory feedback has the same effect in implicit and explicit processing.

In sensorimotor control, feedback by multisensory information affects the quality of motor execution. Among various modality of sensation, the integration of vision and proprioception is important and mismatch between two stimuli causes uncertainty about position and motion (Bays & Wolpert, 2007; Van Beers et al., 1996). As the variability for sensory feedback increases, the execution time slows down to increase the accuracy of movement (Plamondon & Alimi, 1997). However, the latency is always the same regardless of the different degrees of perturbation. The motor control is controlled by internal feedback loops for the position and speed of the hand that is currently moving (Saunders & Knill, 2003; Van Den Dobbelsteen et al., 2003). The VR environment can be considered as an environment in which mismatch between the visual information of the virtual hand and the proprioceptive input from the real body occurs, and cognitive processing continuously occurs to overcome the mismatch between two sensory information in VR. Uncertainty about the estimate of actual state will increase noise in motor command, which will induce higher cognitive load (Bays & Wolpert, 2007; Van Beers et al., 2002).

According to the theory of Bayesian inference, the motor system is determined by prior knowledge of the previous state of body movement (Bays & Wolpert, 2007). So, the motor command reflects the prior state before sensory feedback is influenced on one’s current state and calculates and reflects the prior belief and newly updated sensory information. One of the important factors affecting the variability is the predictability of the next trial. If the subsequent trial is predictable, new updates to previous knowledge are not required. However, if each trial is presented in an unpredictable mode, the motor system needs to continuously update the prior knowledge and recalculate motor command.

The motor control system is a system that adapts very quickly and dynamically to the feedback provided. Therefore, it is thought that the difference between the new prediction model and the current feedback is calculated and reflected immediately based on the prior context, rather than being affected by the single unit value coming in at the moment (Bays & Wolpert, 2007; Limanowski, Kirilina, & Blankenburg, 2017). Sensorimotor adaptation to perturbed feedback occurs within a very short time, and the adapted system exhibits aftereffects. In other words, the motor system to which perturbation is adapted will still operate due to the adapted motor control map even if perturbation disappears (Rohde, van Dam, & Ernst, 2014). Even if a non-adapted situation arises, it is expected that an already adapted strategy will be generalized and applied and will induce perceptual bias (Bedford, 1999; Welch, 1978).

In this study, the response of the cognitive strategy adapted to perturbation in a next trial was compared, by comparing two different conditions when perturbation was provided in a predictably regular sequence and in an unpredictably random sequence.

6.2 Methods

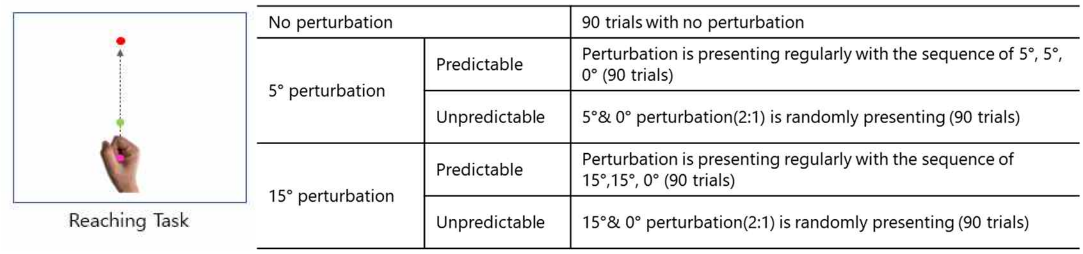
(1) Participants

Total twenty healthy young adults (14 females and 6males) were participated in this study and mean age of participants were 22.2 (SD=2.11). All participants were right-handed from Edinburgh handedness inventory (Oldfield, 1971). The previous experience to use VR was average 1.47. It is confirmed that no one experienced VR more than 2 and they were not exposed to VR frequently in their daily life for all participants. Participants were recruited by open recruitments with flyers and were paid for a certain amount of fee for participation.

(2) Experimental set-up and Procedures

Figure 133. Experimental environment and virtual scene from the participant's perspective

The virtual reaching task was performed in quiet laboratory room which external noise was blocked. The participant was sitting on the chair in front of the desk and wearing HMD and holding the tracker (Figure 1A). HMD is HTC VIVE Pro Eye, VR display was 1440*1600 pixels, 90 Hz refresh rate and visual field was max. 110°. Virtual reality was implemented based on Unity (Figure 1B &1C).



No perturbation		90 trials with no perturbation
5° perturbation	Predictable	Perturbation is presenting regularly with the sequence of 5°, 5°, 0° (90 trials)
	Unpredictable	5°& 0° perturbation(2:1) is randomly presenting (90 trials)
15° perturbation	Predictable	Perturbation is presenting regularly with the sequence of 15°,15°, 0° (90 trials)
	Unpredictable	15°& 0° perturbation(2:1) is randomly presenting (90 trials)

Figure 14. Experimental design and definition of conditions

In the virtual reaching task, each trial starts when a virtual hand touches a green dot and a red dot immediately appears. The task instruction was directed to reach the red dot as quickly as possible but accurately (Figure 2). The conditions for perturbation were 0°, 5°, and 15°, and total 90 trials were performed for each condition. The conditions for 5° and 15° were separated into a condition in which perturbation appeared as a regular sequence (eg, 5°,5°,0°) and a random sequence (Figure 2). The ratio of appearance with and without perturbation was set to 2:1 within 90 trials in both regular and random sequence conditions. At first, assuming that the sensorimotor system will adapt quickly when 5° perturbation occurs twice, 5° trial was defined as an adapted trial, and 0° trial within the same condition was defined as an unadapted trial. The inter-trial interval was randomly presented as 0.5 to 1 s and inter-block interval was fixed 60s considering the fatigue. Each condition was run as a single block, and all blocks were randomized for each subject.

(3) Statistical Analysis

Descriptive statistical analysis was performed to obtain the average values of the average latency, execution time, reaction time (RT), peak velocity, and mean velocity for the reaching movement within each condition. The repeated measure ANOVA was performed to statistically verify differences of RT and mean velocity among conditions. Jamovi 1.0.1.0 was used for statistical analysis.

6.3 Results

Table 12. Results of latency, execution time, RT, peak velocity, mean velocity according to experimental conditions

			Latency (s)	**Execution (s)**	**RT (s)**	**Peak Velocity (m/s)**	**Mean Velocity (m/s)**
No perturbation			0.3152	0.3507	0.6658	1.3705	0.5890
5° Perturbation	Predictable	Unadapted trial (0° Perturb.)	0.3122	0.4276	0.7398	1.3178	0.5206
		Adapted trial (5° Perturb.)	0.3198	0.3925	0.7122	1.3081	0.5286
	Unpredictable	Unadapted trial (0° Perturb.)	0.3192	0.4485	0.7677	1.2968	0.5014
		Adapted trial (5° Perturb.)	0.3176	0.3988	0.7164	1.3124	0.5264

15° Perturbation	Predictable	Unadapted trial (0° Perturb.)	0.3310	0.5477	0.8788	1.2446	0.4078
		Adapted trial (15° Perturb.)	0.3356	0.5418	0.8774	1.2354	0.4075
	Unpredictable	Unadapted trial (0° Perturb.)	0.3326	0.5475	0.8801	1.2300	0.4187
		Adapted trial (15° Perturb.)	0.3386	0.5284	0.8669	1.5399	0.4215

Comparing to the condition that show no perturbation, RT has been increased as the degree of perturbation are increased. If perturbation 5° is predictably coming out, RT was 0.7398s in unadapted trials (0°) and it was 0.7122s in adapted trials (5°). If perturbation 5° is unpredictably coming out, RT was 0.7677s in unadapted trials (0°) and it was 0.7164s in adapted trials (5°).

On the other hand, if perturbation 15° is predictably coming out, RT was 0.8788s in unadapted trials (0°) and RT was 0.8774s in adapted trials (15°). When perturbation 15° is unpredictably coming out, RT was 0.8801s in unadapted trials (0°) and RT was 0.8669s in unadapted trials (15°).

The latency in no perturbation condition was 0.3152. If perturbation 5° is predictably coming out, the latency was 0.3122s in unadapted trials (0°) and it was 0.3198s in adapted trials (5°). If perturbation 5 is unpredictably coming out, the latency was 0.3192s in unadapted trials (0°) and it was 0.3176s in adapted trials (5°). On the other hand, if perturbation 15° is predictably coming out, the latency was 0.3310s in unadapted trials (0°) and it was 0.3356s in adapted trials (15°). If perturbation 5 is unpredictably coming out, the latency was 0.3326s in unadapted trials (0°) and it was 0.3386s in adapted trials (15°).

The latency in no perturbation condition was 0.3152. If perturbation 5° is predictably coming out, the latency was 0.3122s in unadapted trials (0°) and it was 0.3198s in adapted trials (5°). If perturbation 5 is unpredictably coming out, the latency was 0.3192s in unadapted trials (0°) and it was 0.3176s in adapted trials (5°). On the other hand, if perturbation 15° is predictably coming out, the latency was 0.3310s in unadapted trials (0°) and it was 0.3356s in adapted trials (15°). If perturbation 15 is unpredictably coming out, the latency was 0.3326s in unadapted trials (0°) and it was 0.3386s in adapted trials (15°).

Comparing to the condition that show no perturbation, mean velocity to reach the target point has been slow as the degree of perturbation are increased. The mean velocity in no perturbation condition was 0.5890 m/s. If perturbation 5° is predictably coming out, the mean velocity was 0.5206 m/s in unadapted trials (0°) and it was 0.5286 m/s in adapted trials (5°). If perturbation 5 is unpredictably coming out, the mean velocity was 0.5014 m/s in unadapted trials (0°) and it was 0.5264 m/s in adapted trials (5°). On the other hand, if perturbation 15° is predictably coming out, the mean velocity was 0.4078 m/s in unadapted trials (0°) and it was 0.4075 m/s in adapted trials (15°). If perturbation 15 is unpredictably coming out, the mean velocity was 0.4187 m/s in unadapted trials (0°) and it was 0.4215 m/s in adapted trials (15°).

Table 13. Results of repeated measure ANOVA on RT among conditions

	Sum of Squares	df	Mean Square	F	p	η^2_p
Predictability	0.0063	1	0.0063	0.157	0.692	0
Degree of perturbation	24.7176	1	24.7176	653.058	< .001	0.522
Adaptation	0.4167	1	0.4167	6.22	0.013	0.01
Predictability ✻ Degree of perturbation	0.4632	1	0.4632	11.393	< .001	0.019
Predictability ✻ Adaptation	0.1832	1	0.1832	4.241	0.04	0.007
Degree of perturbation ✻ Adaptation	0.3794	1	0.3794	8.894	0.003	0.015
Predictability ✻ Degree of perturbation ✻ Adaptation	0.0489	1	0.0489	1.158	0.282	0.002

There was no statistically significance in predictability effect (predictable vs. unpredictable) (F=0.157, *p*=.692). However, there were statistically significance in degree of perturbation (perturbation 5° vs. 15° condition) and adaptation (adapted trials vs. unadapted trials) (F=653.058, *p*<.001; F=6.22, *p*=.013). Interaction effect was statistically significant in predictability * degree of perturbation (F=11.393, *p*<.001), in predictability * adaptation (F=4.241, *p*=.04) and in degree of perturbation *adaptation (F=8.894, *p*=.003). There was no statistical significance in interaction effect among predictability, degree of perturbation, adaption (F=1.158, *p*=.282).

Table 14. Results of repeated measure ANOVA on mean velocity among conditions

	Sum of Squares	**df**	**Mean Square**	**F**	**p**	**η^2p**
Predictability	5.20E-04	1	5.20E-04	0.0861	0.769	0
Degree of perturbation	13.55267	1	13.55267	1786.92	< .001	0.749
Adaptation	0.00119	1	0.00119	0.0696	0.792	0
Predictability ＊ Degree of perturbation	0.37819	1	0.37819	48.1939	< .001	0.074
Predictability ＊ Adaptation	0.02798	1	0.02798	4.1575	0.042	0.007
Degree of perturbation ＊ Adaptation	0.08733	1	0.08733	10.7455	0.001	0.018
Predictability ＊ Degree of perturbation ＊ Adaptation	0.00891	1	0.00891	1.2481	0.264	0.002

There was no statistically significance in predictability effect (predictable vs. unpredictable) (F=0.0861, *p*=.769) and adaptation effect (adapted trials vs. unadapted trials) (F=0.0696, *p*=.792). However, there were statistically significance in degree of perturbation (perturbation 5° vs. 15° condition) (F=1786.92, *p*<.001). Interaction effect was statistically significant in predictability * degree of perturbation (F=48.1939, *p*<.001), in predictability * adaptation (F=4.1575, *p*=.042) and in degree of perturbation *adaptation (F=10.7455, *p*=.001). There was no statistical significance in interaction effect among predictability, degree of perturbation, adaption (F=1.2481, *p*=.264).

In perturbation 5°, RT was slower in the unpredictable condition than in the predictable condition. On the other hand, in perturbation 15°, RT was similar in predictable and unpredictable conditions. Adapted trials (5° or 15° perturbation) showed faster RT in unpredictable condition than predictable condition, and unadapted trials (0° perturbation) showed slower RT in unpredictable condition than predictable condition. Finally, when the perturbation was 5°, the RT was slower in the unadapted trial than in the adapted trial, but when the perturbation was 15°, there was no difference in RT between the adapted and unadapted trials.

In perturbation 5° and 15°, mean velocity was not significantly different in the unpredictable condition and predictable condition. Mean velocity was faster in unpredictable condition on adapted trials but it was faster in predictable condition on unadapted trials. However, there was statistical significance in interaction effect of predictability and adaptation. In both perturbation 5° and 15°, mean velocity of reaching was not different in adapted and unadapted trials.

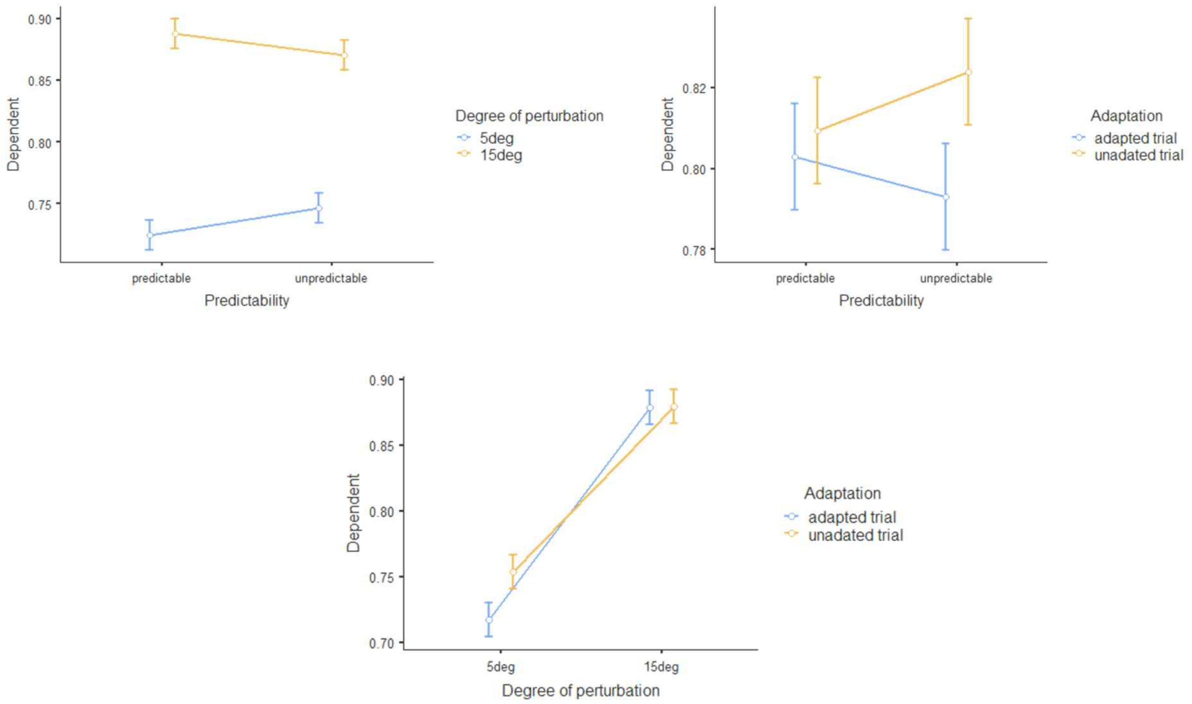


Figure 15. plots for estimated marginal means of RT on interaction effect of two factors

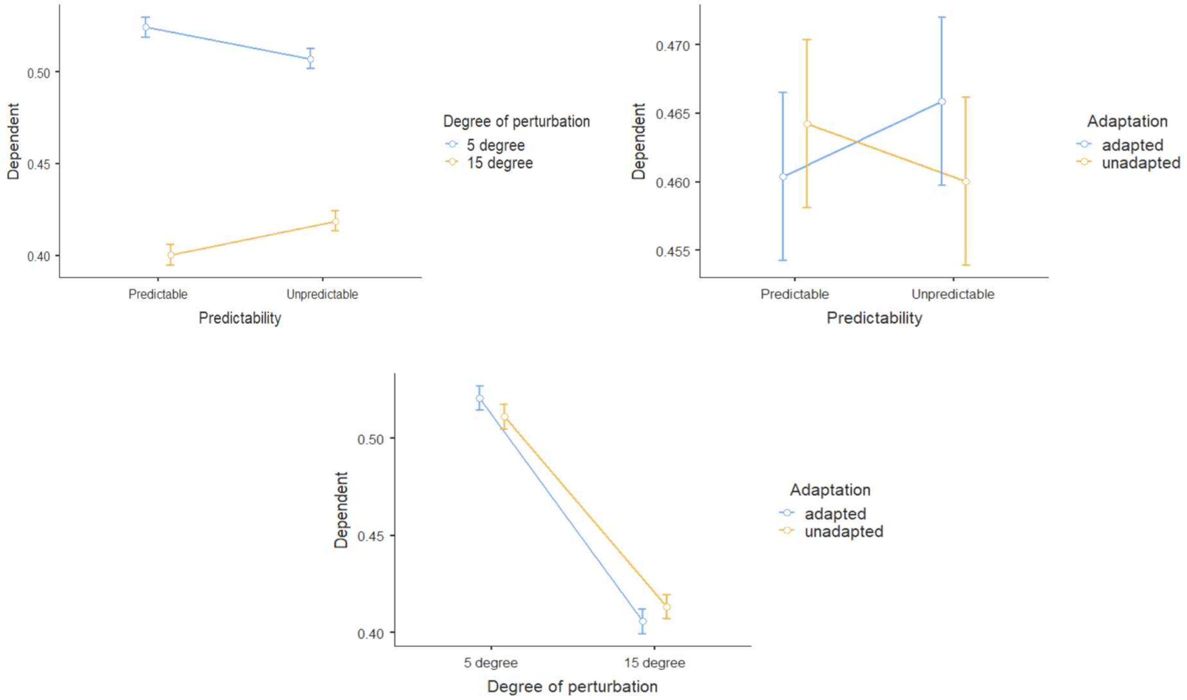


Figure 16. Plots for estimated marginal mean of mean velocity on interaction effects of two factors

6.4 Discussion

The VR environment is considered an environment in which there is increased cognitive load generated during the sensorimotor control process as compared to the real environment (Moreno et al., 2019; Plechatá et al., 2019). In general, when one interacts with the environment and objects in real world, sensorimotor control is regarded as an adapted state because the feedback on one's action operates in a predictable fashion. As one can walk or manipulate an object in a real environment, most sensorimotor control is operated without any cognitive overload. Mismatched information that is not identical to the actual feedback causes the cognitive load depending on the degrees of spatial and temporal perturbation of sensory feedback (Farrer et al., 2008; Foulkes & Miall, 2000a; Van Den Dobbelsteen et al., 2003). In the results of this study, as the degree of perturbation increased, the reaction time (RT) increased and the mean velocity decreased, showing consistent results on every condition within the same degree of perturbation. As the variability of the sensory feedback in the sensorimotor control system increases, the strategy is to take a longer RT and slow down the speed of movement to improve the accuracy (Bays & Wolpert, 2007; Todorov, 2004).

It is true that the magnitude of spatial and temporal perturbation also affects sensorimotor control. However, this study tried to investigate how the predictability of sensory feedback affects the use of cognitive strategies on reaching movement. According to the internal model explaining the sensorimotor control process, the system load increases as the uncertainty of feedback noise increases (Wolpert et al., 1995). The most influential factor on the uncertainty of noise is predictability for sensory stimuli (Bays & Wolpert, 2007).

The results of this study showed that the predictability effect was not statistically significant. However, it was found that there was a statistically significant interaction effect between predictability and degree of perturbation ($F=11.393$, $p<.001$). As a result of post-hoc verification, the predictability effect was found to be statistically significant only in perturbation 5 degrees (implicit process). That is, in implicit processing, RT was found to be slower in the unpredictable condition than in the predictable condition. On the other hand, the mean velocity was also slower in the unpredictable condition than the predictable condition

Motor control is achieved by calculating the error difference between the predicted motor command and sensory feedback in the implicit process. When the next trial is predictable compared with the previous trial, the cognitive load given to the error estimation is low, but when it is presented unpredictably, the cognitive load increases (Bays & Wolpert, 2007). The results of this study support this claim.

On the other hand, in explicit processing, it was found that there was no statistically significant difference in RT and mean velocity between predictable and unpredictable conditions. In the explicit process, it was not affected by the predictability of perturbation because explicit control operates based on the error between the current target location and sensory feedback (Taylor & Ivry, 2011).

Adaptation will occur to reduce errors with the predicted command by receiving feedback information on the implicit process (Taylor et al., 2014). Depending on the frequency of 5 degrees and 0 degrees in one condition, sensorimotor adaptation to perturbation will be different. In this study, the appearance ratio of 5 degrees and 0 degrees perturbation per condition was 2:1. As the sensorimotor system adapts to movement within a very short time (Foulkes & Miall, 2000b; Taylor & Ivry, 2011), it would adapt to the 5 degree perturbation which frequently appeared. Interaction effect on degree of perturbation and adaptation was statistically significant (F=8.894, *p*=.003). When perturbation was 5 degrees (implicit process), the RT between adapted and unadapted trials were significantly different. However, there is no significant difference between adapted and unadapted trials when the perturbation was 15 degrees (explicit process). It is suggested that the internal model that estimate the motor command for the next trial by adapting to the previous trial was obviously observed in implicit processing.

In the 5 degrees perturbation which was regarded as an implicit process, quick adaptation was attempted using the internal model. The next trial was based on previously adapted motor control; therefore, when the unexpected stimulus came out, the strategy to reduce the speed of one's movements and increase the accuracy was taken (Van Beers et al., 2002). However, if the unadapted stimulus came out unpredictably, a strategy was used to further increase the accuracy of the operation by slowing down the speed to reduce the error between the predicted motor control and the feedback.

In the explicit process, the sensorimotor control was performed based on the error difference between the actual target and the current position of the hand in VR (Taylor & Ivry, 2011). Since the deviation of sensory feedback was explicitly felt, it is thought that a strategy to slow down the speed and increase the accuracy of movement is used in every trial regardless of predictability and adaptation.

In conclusion, the uncertainty of sensory feedback due to visual perturbation in VR causes the cognitive load to take a new cognitive strategy. In particular, it appears that the uncertainty of sensory feedback is affected more in the implicit process of the internal model than in the explicit. By developing

VR technology, a considerable level of visual fidelity is possible. However, the unpredictable visual perturbation of VR scene still requires the switching of an appropriate cognitive strategy to act on it, and a cognitive load is induced as a result. The unpredictability in the implicit process of sensorimotor control can be regarded to increase the noise of sensory feedback.

In a future study, it is necessary to investigate how the entropy of sensory noise affects sensorimotor learning adaptation by adjusting the appearance ratio between the adapted trial and the undapted trial within a condition. In addition, it is expected that it can be used as an index to measure the efficiency of cognitive functioning by identifying the pattern of the use of the cognitive strategy used on sensorimotor adaptation in VR.

CHAPTER 7. Conclusion

7.1 Summary of Findings

Although diverse metaverse-based platforms with HMD are being developed through technological development, the research of the characteristics of human cognitive mechanism in such a digital environment has not been emphasized. The cognitive mechanism in VR and the real environment would be totally different. Performing a task in VR is a situation that requires additional cognitive load for sensorimotor control by adapting behaviors to the VR environment in addition to the cognitive load required for the task itself. It is necessary to systematically consider factors that give cognitive load in virtual reality, and in particular, it is necessary to explore the aspect of cognitive load caused by information mismatch.

In addition, it is a significant advantage that it is able to observe behavioral characteristics to perform a task in the virtual space by replacing the pencil and paper assessment. It can be proposed as an ecologically valid neuropsychological evaluation in terms of veridicality and verisimilitude. The VR environment has the advantage of being more cost effective than setting up the evaluation context in the real environment (Moyle, Jones, Dwan, & Petrovich, 2018; Riva, 1997). In addition, when performing tasks in a real environment, the cognitive deficits would be not shown in performance because we have automatically adapted and habituated to the nature of tasks in our daily life for a long time. Especially, it takes a longer time for cognitive deterioration to appear functionally in the elderly, so it is difficult to follow up for early cognitive deterioration (Farina et al., 2018). It would be useful for screening cognitive decline in the early stage.

The VR environment is regarded as an environment that challenges the cognitive capacity, so it can be called cognitive treadmill. In this reason, giving a challenge in virtual environment with high cognitive load can be a method to increasing the discriminatory power as a neuropsychological evaluation. Just as we clinically assess the cardiorespiratory endurance while giving the maximum limit of capacity to the heart when measuring its function, providing an evaluation context that can challenge the limits of cognitive function also enhances the discriminatory power of cognitive evaluation.

It was found that there was no relationship between age and educational background that determines the outcome of performance in immersive VR, and only the general cognitive level influences on performance in VR for the elderly group. While non-immersive VR is affected by age and academic background in user interface manipulation and organization in virtual space, immersive VR with HMD is user interface free and has been less influenced by age and educational background by constructing the environment similar to operation in real life.

In the elderly compared to young adults, it is difficult to perform tasks in virtual reality because there is a cognitive load due to information mismatch between multi-sensory information to process the sense of presence in VR. In addition, since sensorimotor control in the VR is somewhat different from that in the real environment, a new re-adaptation is required. Re-adaptation of sensorimotor control in VR induces additional cognitive load in performing tasks, and it can be thought that the elderly are challenged by such motor control re-adaptation. In particular, the unpredictability of visual feedback in implicit motor control increases the uncertainty in predicting motor control and it induces cognitive load.

Furthermore, sensorimotor adaptation in virtual reality takes place within a short time period than expected, and when an unexpected stimulus comes into the adapted motor control process, a strategy is taken to adapt it. According to the speed and accuracy trade-off, if an unadapted sensory stimulus comes in, the strategy for motor control is to slow down the speed and try to increase the accuracy of the movement. Especially, when it comes out as an unpredictable sequence, it was observed that the speed of movement become more slower in new strategy. Therefore, it was found that when sensory feedback is irregularly presented in virtual reality, a cognitive strategy is adopted to control movement within it, and task execution time is slower than performing tasks in the real environment.

More important than the technical fidelity problem in virtual reality implementation, the standard of technical implementation should come from understanding human cognitive mechanisms. In particular, the human brain should be viewed from the perspective of a predictive brain. That is, it works in a way that predicts the feedback given in the environment and reduces the error between the predicted representation and the actual feedback. From this point of view, the method of reducing the noise of feedback reduces the cognitive load and helps a more focused cognitive process. In this case, the noise is affected by the uncertainty of the feedback information. As the mismatch of information increases, that is, as unpredictability increases, the uncertainty of noise increases that cause cognitive overload to handle. In the development of various types of immersive or non-immersive digital devices, if we understand the characteristics of the brain mechanism, it will be possible to realize more useful and convenient virtual technology for humans.

7.2 Future Direction of Research

The VR task proposed in this study can be considered as an alternative methodology that can evaluate cognitive functions more discriminatingly by inducing a cognitive challenge. However, as the classical neuropsychological evaluations have been developed based on conceptual rigor and validity criteria for cognitive deficits in the brain, VR-based evaluations also need to be reviewed from the cognitive scientific aspects. In future research, it is necessary to prove its validity through comparison with standard neuropsychological evaluation or comparative analysis with brain imaging results. In addition, it is also necessary to examine how reliably match the clinical judgment of experts with the behavioral characteristics appearing in VR.

The advantage of VR based evaluation is that all information behaved within the VR environment can be digitalized and stored. Through this advantages, various quantitative analyzes of human behavioral characteristics will be feasible. In addition, it is worth trying to learn patterns such as human movement trajectory or sequence by applying artificial intelligence machine learning technology and classify them according to cognitive functions. Furthermore, automation of evaluation can be implemented, and as a result, automatic coding and interpretation of cognitive evaluation would be possible as well.

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국문 초록

가상현실 내 정보불일치를 활용한 인지기능 평가
: 탐색적 고찰

본 박사논문의 목적은 가상현실 내에서 발생하는 정보불일치에 대해서 알아보고, 정보불일치로 인한 인지적 반응을 인지기능 평가에 활용할 수 있는 방안을 고찰하고자 함이다. 가상현실 주방과제를 구현하여 과제 수행 중 나타나는 움직임과 인지작용의 특성을 알아보고자 하였다. 또한 VR에서 과제수행 시 나타나는 인지 부하의 요인을 탐색하였다. 특히, 감각운동 조절 측면에서 가상현실 내 발생하는 정보불일치로 인한 인지 과부하를 살펴보았다.

첫째, 가상현실과 실제환경에서 작동하는 인지과정이 어떻게 다른지 알아보기 위해 두 환경 간의 과제 수행 차이를 비교하였다. 젊은 성인 그룹에서는 어려운 주방과제 수행 시 가상현실과 실제환경 간의 수행시간에 유의한 차이가 있었지만 쉬운 주방 과제에서는 차이가 없었다. 반면 노인 집단에서는 과제의 난이도와 관계없이 두 환경 간의 수행 시간에 상당한 차이가 있었다. 노인의 경우 가상현실에서 감각운동 조절의 어려움을 보였다. 즉 노인의 경우 젊은 성인에 비해 가상현실 내에서의 감각운동 조절이 더 어렵기 때문에 이로 인한 인지적 부하가 과제 수행 자체의 인지적 부하에 가중되어 과제 난이도가 어려워지면 인지용량의 한계를 초과하게 된다.

둘째, 가상 주방과제 수행 시 인지기능이 저하됨에 따라 갑자기 휙 움직이는(jerky) 패턴을 보이는 것으로 나타났다. 이는 인지기능이 저하된 노인의 경우 환경에 대한 예측력이 저하되어 최소 저크운동 조절(minimal jerk movement control)에 어려움이 있음을 시사한다. 또한 인지기능이 높은 그룹보다 인지기능이 낮은 노인 그룹의 경우 과제가 완료될 때까지의 일련의 움직임 단계가 더 많았다. 인지기능이 저하됨에 따라 비효율적이고 분주한 움직임을 보인다고 할 수 있다. 또한 다중회귀분석 결과, 노인이 가상현실 주방과제를 효율적으로 수행함에 있어 연령 및 학력 보다는 인지기능이 가장 영향을 미치는 요인으로 나타났다. 즉 가상현실 기반 과제수행은 순수 인지기능만을 평가하는 새로운 대안으로 제시할 수 있다.

마지막으로 감각운동 피드백의 예측불가능성(unpredictability)이 가상현실에서 인지부하를 유발하는 방식을 알아보고자 하였다. 섭동의 예측 가능성에 따른 반응 시간과 이동 속도를 암묵적 5° 와 명시적 15° 섭동 조건에서 각각 측정하였다. 그 결과 암묵적 운동 제어 시 섭동의 변화를 예측할 수 없을 때 움직임의 정확도를 높이기 위해 움직임이 느려지는 전략(accuracy and speed trade-off)을 사용하는 것으로 나타났다. 즉, 감각운동조절 과정 상에서 정보 불일치로 인한 예측 불가능성에 대해 우리의 뇌는 다른 인지전략을 취한다고 설명할 수 있다.

결론적으로 가상현실은 기술적 충실도(fidelity) 문제로 인해 감각 피드백이 예측 불가능하고 가변적이기 때문에 실제 환경보다 더 많은 인지 부하를 유발한다. 특히 가상현실에서의 감각운동 조절은 실제환경에서 인간의 운동 시스템이 적응된 방식과는 다르다고 볼 수 있다. 즉 가상현실 내에서는 감각운동 시스템이 예측할 수 없는 환경에 적응하기 위해 다른 인지 전략을 취하게 된다. 환경에 따른 효율적인 인지전략의 전환은 중앙 집행기능(central executive)과 관련 있으며, 이러한 특징을 활용한 가상현실기반 과제는 새로운 인지기능 평가의 대안으로 제시할 수 있다.

주요어: 가상현실, 감각운동조절, 노인, 예측가능성, 정보불일치
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