論 文 の 内 容 の 要 旨

論文題目　A Study of Redirected Walking With Individual Characteristics of the Sensory Systems
（感覚系の個人特性を考慮したリダイレクテッドウォーキングの研究）

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Redirected walking (RDW) is a set of technologies that enables users to walk freely within a virtual environment (VE) by controlling the spatial correspondence of virtual and real environments.
The ultimate goal of the RDW is to enable users to explore an arbitrary virtual reality (VR) space in a room-scale real space while maintaining a natural gait. Extensive research has been conducted in this field over the past 20 years, and various algorithms, techniques, and evaluation methods have been proposed. However, there are still numerous unsolved problems in achieving the ultimate goal of RDW.

One of the major problems of RDW is detection thresholds, which are the smallest manipulations that a user can detect.
In general, manipulations of RDWs are performed below a detection threshold because performing manipulations beyond the threshold may decrease the sense of presence and cause cybersickness.
A large number of studies have estimated the value of the detection threshold or proposed methods to estimate the detection threshold.
According to these studies, the detection threshold is not constant, and it is strongly affected by equipment, VEs, and individual differences.
In particular, it has been shown that there are significant individual differences in detection thresholds.
The effectiveness of the conventional RDW method that uses only visual manipulations is limited, and it is not always possible to compress an arbitrary VR space into a room-scale real space using manipulations below the perceptual

threshold.

In this work, we addressed the aforementioned issues using findings from physiology and psychology.
We addressed the issues of individual differences in detection thresholds in terms of sensory characteristics (Chapter 3).
In addition, on the basis of physiology, the effects of an RDW technique were estimated using physiological and behavioral indices (Chapter 4).

We attempted to improve the limited effectiveness of RDW using senses other than vision.
We used the findings of cognitive science for this purpose, i.e., spatial perception consists of vision, vestibular perception, somatosensory perception, and hearing.
In recent years, the maximum likelihood estimation (MLE) model has been presented as a versatile model of sensory integration in the field of perceptual psychology.
We used the MLE model to develop the novel RDW methods, which used vestibular perception (Chapter 5), auditory perception (Chapter 6), and haptic perception (Chapter 7).
We evaluated these methods using the estimation methods proposed in Chapters 3 and 4 and the conventional psychophysical method.

In Chapter 3, we evaluated the relationship between detection thresholds, cybersickness, and perceptual characteristics.
In the field of developmental psychology, it is well known that there is a relationship between perceptual characteristics and spatial perception.
Therefore, we considered that there is a relationship between sensory characteristics and RDW, which is a type of spatial perceptual manipulation.
A psychophysical experiment was conducted to estimate the detection thresholds of an RDW technique, and a questionnaire was used to evaluate the individual perceptual characteristics.
Our results suggested that participants with a higher propensity for sensory sensitivity and sensory avoidance were more likely to notice RDW manipulation.

In Chapter 4, we investigated the relationship between redirection thresholds and physiological and behavioral indices and discussed the method for inferring

redirection thresholds based on physiological and behavioral indices.
The pupil diameter and microsaccades were selected as physiological indices, and walking speed and head sway were selected as behavioral indices.
Experimental results showed a correlation between walking speed, head sway and redirection thresholds.

In Chapter 5, based on the MLE theory, we hypothesized that reducing the reliability of vestibular sensation would improve the effectiveness of RDW and reduce cybersickness.
Noisy galvanic vestibular stimulation (nGVS) was used to reduce the reliability of vestibular sensation.
We conducted a psychophysical experiment to estimate the detection thresholds of curvature gain and measure cybersickness under two nGVS conditions.
The results suggested that nGVS might affect the detection thresholds of curvature gain.

In Chapter 6, we first investigated whether MLE could be applied to incongruent visuo-auditory integration in a VR environment.
Then, we proposed a novel method that introduced visual noise and incongruence between the visual and auditory cues of an object in a VE while applying curvature gain.
We verified the effectiveness of this method by comparing it with existing psychophysical methods.

Finally, in Chapter 7, we explored the possibility of visuo-haptic RDW.
We verified the effectiveness of this method through psychophysical and behavioral evaluations.
Then, we created {¥it Unlimited Corridor}, which was a type of media art based on visuo-haptic RDW. Unlimited Corridor enabled users to freely explore an immersive corridor by touching walls or handrails.
In addition, we conducted a workshop about Unlimited Corridor.
People associated with VR work, curators, attendants, individuals, and developers participated in the workshop to discuss the operation and experience of Unlimited Corridor in an art museum.
This workshop enabled us to identify the strengths and challenges of VR exhibitions in general society, such as in museums.

Overall, even though there were individual differences, the results showed that perceptual characteristics influenced the effectiveness of RDW and there was a correlation between behavioral indices and the perceptual threshold of RDW. Furthermore, psychophysical experiments and behavioral indices showed that our new multimodal RDW technology improved the effectiveness of RDW.

These findings emphasize the importance of considering individual differences in perception and optimizing the type and amount of stimuli for each individual in the design of virtual experiences.