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Identification of Shape Characteristics of the Field of View in Patients with Unilateral Spatial Neglect Using Virtual Reality Environments

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Abstract**—Unilateral spatial neglect (USN) is a higher cognitive dysfunction that can occur following a stroke. It is characterized by the impairment in locating, reporting, reacting to, and directing attention toward stimuli presented on the side opposite to the brain lesion. Although it is understood that USN results from the misdirection of attention, the influence of a patient's attentional state on the symptoms of neglect remains unclear. This study aimed to explore the relationship between attention and neglect by identifying the position and size of the attentional area, as well as the shape characteristics of the field of view (SCFV), using 3D virtual reality (VR). We assessed these characteristics based on the patient's recognition or non-recognition of displayed objects, reaction time, and gaze behavior within an immersive VR space. The results indicated that the relationship between attention and neglect symptoms varied among patients, suggesting the potential for personalized rehabilitation based on each patient's attentional state.**

I. Introduction

USN is a higher order brain dysfunction that affects approximately 50% of stroke patients [1][2]. Patients with USN are unable to respond to stimuli on the side of the body opposite to the brain lesion [3]. Typically, when the lesion is on the right side of the brain, the left side is neglected [4]. Patients with USN are unable to direct their attention toward the neglected side, which leads to significant difficulties in performing daily activities. For instance, patients may fail to eat half of a meal or fail to look to the neglected side when crossing a street [5].

The symptoms of USN are spatially specific. Two distinct types of neglect are observed: proximal (short distance) spatial neglect and distal (long distance) spatial neglect. It is estimated that between 53% and 71% of patients with USN exhibit one of these forms of neglect [6][7][8][9]. However, traditional paper-based assessments, such as the internationally recognized Behavioral Inattention Test (BIT) [10], have limitations in capturing the full range of symptoms associated with spatial neglect, particularly those related to proximal spatial neglect.

Considering this background, we developed a system for the quantitative assessment of neglect symptoms in both proximal and distal spaces using immersive VR and evaluated it on patients [11]. This system enabled the quantitative assessment of the neglected areas in patients with USN in three dimensions and the measurement of non-exploratory and exploratory cognitive abilities. Non-exploratory cognitive abilities refer to those demonstrated when the neck is immobilized, while exploratory cognitive abilities are observed in a free state [12]. However, while it has been revealed that exploratory cognitive ability can be substituted by the ability to rotate the neck during object search, the physical quantities related to non-exploratory cognitive abilities remain unclear. Therefore, the indicators necessary for improving non-exploratory cognitive abilities are still unknown and their identification is needed.

To address this, we focused on gaze information to identify non-exploratory cognitive abilities. One study has shown that the direction of gaze and attention generally align in healthy individuals [13]. However, some research indicates that gaze and attention do not always coincide, despite this being a common assumption [14]. This discrepancy suggests the existence of two types of neglect: one where the gaze does not reach the object of attention, and another where it does. This variation is likely due to differences in each patient's Attention-Enabled Area (AEA). Humans perceive not only the area directly at the gaze point but also the surrounding areas as part of their visual field, referred to as AEA. Based on this, we hypothesized that the size and shape of the AEA around the gaze point vary among patients. In the context of USN, while studies have examined gaze position, there has been limited research on the AEA. Therefore, determining the position and shape of the AEA relative to the gaze point for each patient, defined as the shape characteristics of the field of view (SCFV), is crucial.

The purpose of this study was to identify the SCFV for each patient based on a three-dimensional evaluation of neglect.

II. System Overview

The system comprises a head-mounted display (HMD) (VIVE Pro Eye, HTC, Taiwan) [15] and a laptop, with the immersive VR environment developed using Unity (Unity Technologies, USA). Participants view a room within the immersive VR space from a first-person perspective, where visual stimuli are presented at various coordinates. The laptop

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records whether the stimuli are recognized, along with the position coordinates, to identify neglected areas. To document responses, participants indicate their recognition of a stimulus presentation orally, and the recorder enters the responses on a laptop with a keyboard. Visual stimuli are presented at three different heights (low, middle, and high, see Figure 1(A)) and four different distances (0.5, 1.0, 3.0, and 6.0 meters), at 15° intervals (stimuli are presented at the intersections of radiating lines and concentric circles as shown in Figure 1(B)). The system also captures the patient's gaze direction using the HMD during the neglect assessment. Additionally, the delay between stimulus presentation and patient recognition is calculated for each position, providing a measure of reaction time.

The system generates a three-dimensional neglect map for each patient (see Figure 2). Given that the viewing angle of the HMD, with the neck immobilized, ranges from 30° to −30° (as illustrated in Figure 1(B)), the neglect map for the neck-immobilized condition is displayed within this range. Figure 3 presents the neglect map at a selected distance. As demonstrated in Figure 3, this study identifies and examines the SCFV within the 30° to −30° visual field range in the immobilized neck condition at various distances. In the example displayed in Figure 3, the blue range is the recognized area of this patient, the pink range is the neglected area.

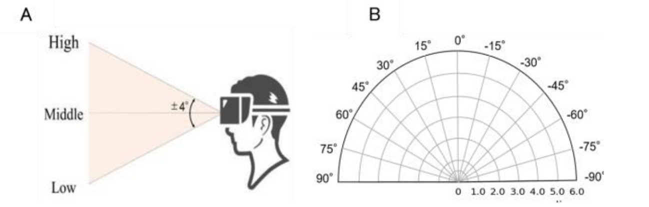

Figure 1. (A) Description of the three levels of height, (B) Position of the appearance of the stimulus

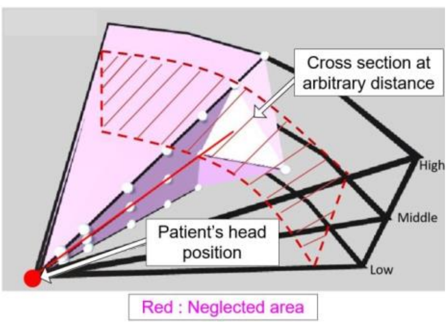

Figure 2. 3D neglect map (Fixed-neck condition)

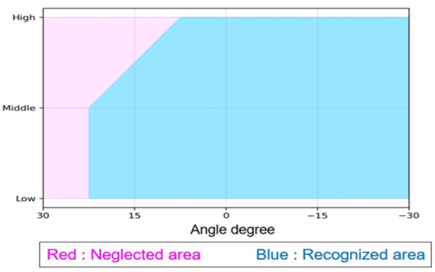

Figure 3. Example of a neglect map of cross section at arbitrary distance

III. Examination of the Determinants of Disregard by Acquiring Eye Gaze Information

Three stroke patients with left USN (hereinafter referred to as Patients A, B, and C) were assessed using the described system, with the neck immobilized, to evaluate neglect. Gaze data were collected during the assessment. Patients A and C detected the stimulus without directing their gaze towards it, whereas patient B directed their gaze towards the stimulus but ignored it, suggesting differences in their SCFV (see Figure 4). Specifically, Patient A had a larger AEA on the neglected side compared to Patient B. Patient C did not exhibit any neglected areas under the neck fixation condition, suggesting a substantially larger AEA. Patient C was nevertheless not excluded from the study due to demonstrating neglect in the condition without neck fixation. These findings indicate that recognition or neglect is not solely dependent on gaze position. Therefore, can be inferred that each patient's individual SCFV potentially plays a significant role in recognition and neglect.

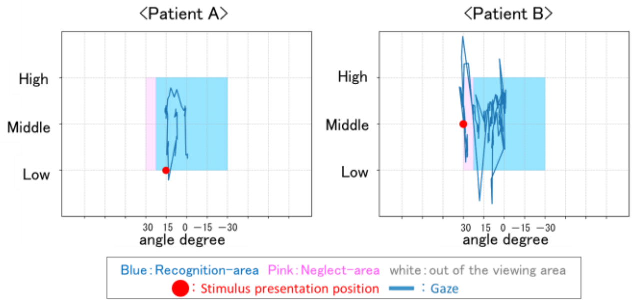

Figure 4. Recognition and neglected areas and gaze in Patients A and B

IV. Development of a Method for Identification of SCFV

In healthy individuals, all presented stimuli within the AEA were identified, resulting in consistent reaction times regardless of the stimuli's position. However, patients with USN may need to shift their gaze to search for stimuli that are not recognized within their AEA, potentially causing delayed reaction times due to eye movement. Thus, we hypothesized that reaction time length could be used to identify the SCFV.

First, we confirmed that reaction times did not vary with the position of visual stimuli in healthy elderly individuals. We conducted tests to evaluate their response to visual stimuli and established a criterion for reaction time. The SCFV were then determined based on the reference reaction times obtained from these healthy elderly individuals.

A. Gaze movement and reactivity evaluation test in healthy elderly individuals

- Method

  Twelve healthy elderly individuals (average age 71.1 ± 3.9 years, six males and six females) participated in this study. Using the system described in Section 2, we measured their recognition and reaction times to visual stimuli under neck immobilization conditions. It was confirmed that all visual stimuli presented were within the visual field of these individuals. The positions of the visual stimuli presentations are shown in Figure 5, where the red circles indicate the locations of the visual stimuli. Visual stimulus is presented three times at each of the 15 presentation positions presentation position randomly. The visual stimulus is presented until the subject answers whether it is recognized or not, after which the visual stimulus is presented at the next random presentation position.

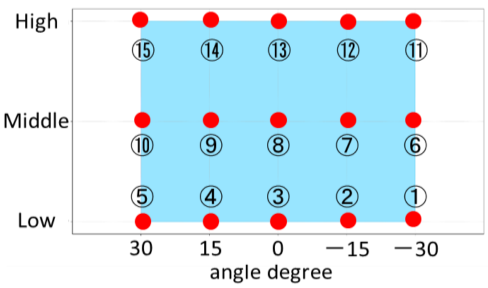

Figure 5. Visual stimulus presentation position

- Result

All healthy individuals recognized the visual stimuli. The reaction times for one subject at each presentation location are shown in Figure 6. The reaction times for the 15 presentation locations did not significantly differ by location (Kruskal–Wallis test, $p = 0.05$, Figure6. Position (8) in Figure 5 corresponds to the initial gaze position, indicating that the object presented at this position should be recognizable without a gaze search. Although, we anticipated that reaction times would increase with gaze search. Findings showed that the reaction time for position (8) was consistent with other positions, suggesting that healthy elderly individuals can recognize any object within their visual field without needing to search. This observation was consistent across all 12 healthy elderly individuals. These findings demonstrate that healthy elderly individuals do not experience delays in reaction time, regardless of the stimulus presentation position within their visual field.

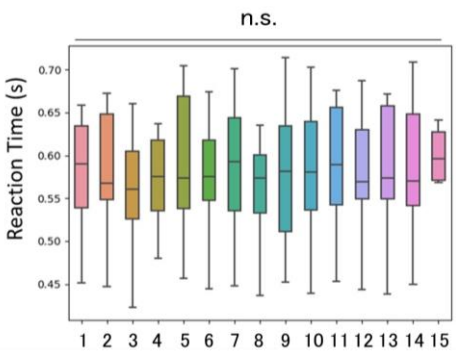

Figure 6. Average reaction time for each stimulus presentation position in healthy elderly individuals

B. Extraction of the degree of stimulus response latency

In the previous section, we demonstrated that gaze shifts do not increase the detection area or delay reaction time in healthy elderly individuals. Conversely, it may be expected of patients with USN to shift their gaze to expand their recognition area due to having a limited AEA. To standardize reaction times for different visual stimulus positions in the SCFV method described below, a reference reaction time of 1.039 s was established. This reference was calculated as the average reaction time of healthy elderly individuals, based on the results from their assessments. This standardization allows for a direct comparison of reaction times between patients and healthy elderly individuals.

C. Flow of the SCFV Identification Method

Using the standard reaction time for healthy elderly individuals, obtained in the previous section, the following steps were used to present the SCFV:

Step 1. Calculate the reaction time to the recognition stimulus at each position (see Figure 7).

Step 2. Normalize the reaction time using the reference reaction time of 1.039s established for healthy elderly individuals (see Figure 8).

Step 3. Assign a value of 20 to locations where neglect is observed. Since the maximum normalized reaction time was 10, neglected stimuli, which are not detected, were assigned a doubled value of 20 to represent positive infinity (see Figure 8).

Step 4. Draw contour lines by connecting points with equal reaction times, creating a gradient of the normalized reaction times.

Step 5. Define the area where the contour line is less than 2.5 as having short reaction time and high reactivity (see Figure 9).

By following this procedure, it is possible to identify the SCFV of a patient with USN who shifts their gaze to expand their recognition area.

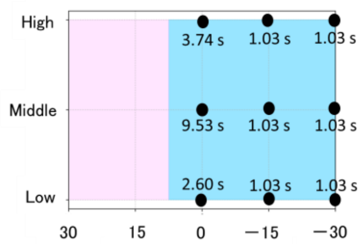

Figure 7. Flow of identification method-Step 1with reaction time of USN patients

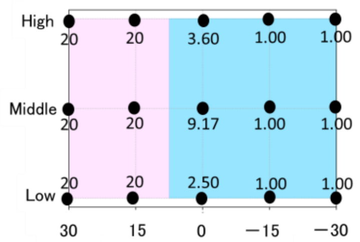

Figure 8. Flow of identification method-Steps 2,3 with scores at each presentation position

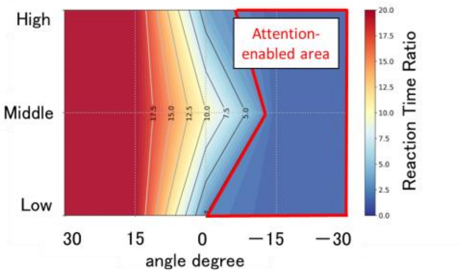

Figure 9. Flow of identification method-Steps 4,5

V. IDENTIFICATION TEST OF SCFV METHODS IN PATIENTS WITH USN

A. Method

The study included 14 stroke patients (Patient I to XIV) with left USN. Using the same system, we measured stimulus recognition and reaction time under cervical fixation conditions. It was ensured that all visual stimuli presented were within the visual field of a typical subject under these conditions. Visual stimuli were presented at distances of 0.5m, 1.0m, 3.0m, and 6.0m. The SCFV for each distance was determined and plotted on the neglect map.

B. Result

In all patients, SCFV identification was possible based on reaction time measurements. As an example, the neglect maps and the geometric properties of the visual field for Patient I are presented in the results (Figures 10 and 11).

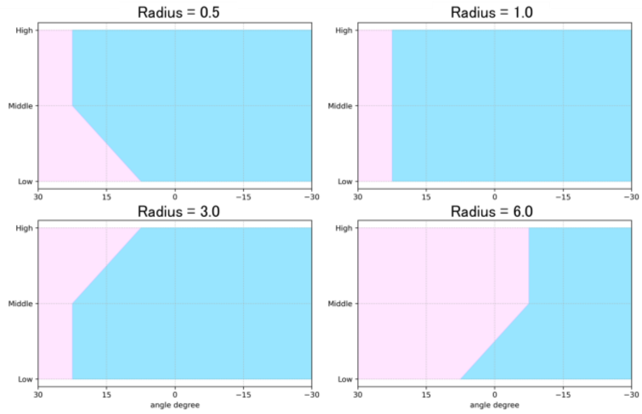

Figure 10. Neglected Maps for Patient I

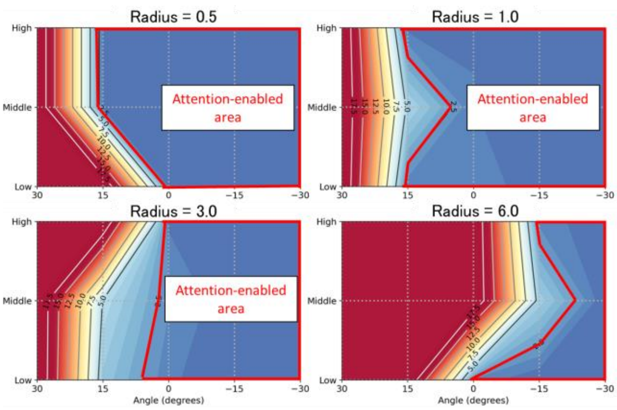

Figure 11. SCFV of Patient I

C. Consideration

The following examples illustrate patients with identical neglected areas but differing AEAs and SCFVs.

- Patient I and Patient II

  The neglect map at a distance of 1m was identical for both Patient I and Patient II, as shown in Figure 12(A). No differences were observed between these two patients on the neglect map. However, when the SCFVs of both patients was identified based on reaction times, as shown in Figures 12(B) and 12(C), respectively, the ratio of the area of the AEA to the total area of the visual field range was determined to be 0.70 for Patient I and 0.76 for Patient II. In this case, Patient II exhibits a wider AEA.

- Patient III and Patient IV

  The neglect map at a distance of 6m for both Patient III and Patient IV is shown in Figure 13(A), with no observed differences between the two. In contrast, the SCFVs of Patient III and Patient IV, identified based on reaction times, are shown in Figures 13(B) and 13(C), respectively. The configurations of the AEAs differ significantly between these two figures. The ratio of the area of the AEA to the total area of the visual field range was determined to be 0.36 for Patient III and 0.31 for Patient IV. In this case, Patient III exhibits a wider AEA.

- Patient V and Patient VI

  The neglect map at a distance of 3m for both Patient V and Patient VI is shown in Figure 14(A), with no differences observed. However, the SCFVs of Patient V and Patient VI, identified based on their reaction times, are illustrated in Figures 14(B) and 14(C), respectively. These figures demonstrate that the shapes of the AEAs are distinctly different. As shown in Figure 14(C), the AEA configuration between Patient V and Patient VI varies significantly. The ratio of the area of the AEA to the total area of the visual field range was determined to be 0.51 for Patient V and 0.42 for Patient VI. In this case, Patient V exhibits a wider AEA.

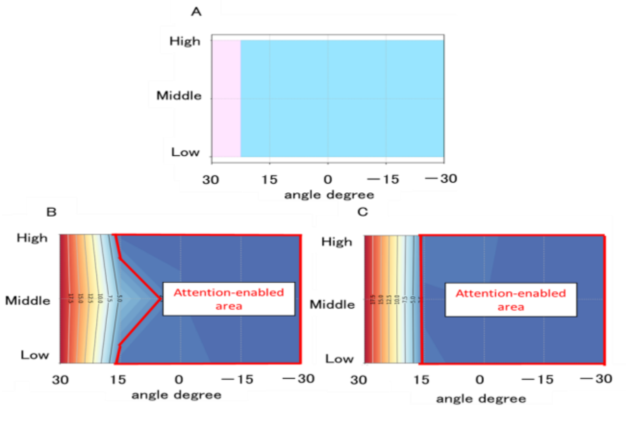

Figure 12. (A) Neglect Map of Patients I and II, (B) SCFV of Patient I, (C) SCFV of Patient II

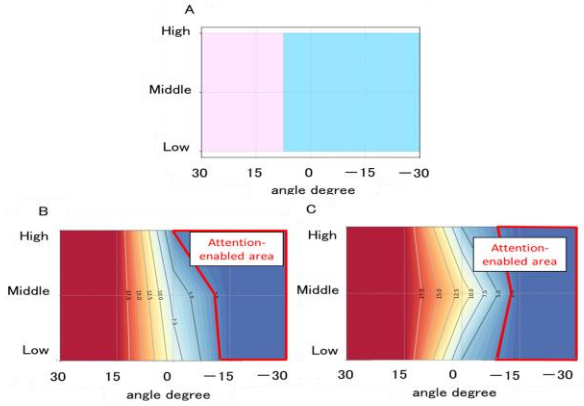

Figure 13. (A) Neglect Map of Patients III and IV, (B) SCFV of Patient III, (C) SCFV of Patient IV

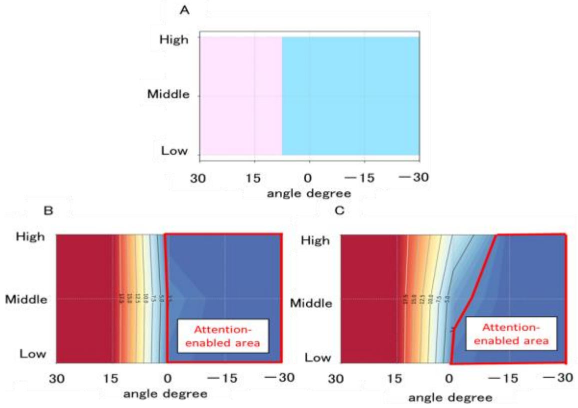

Figure 14. (A) Neglect Map of Patients V and VI, (B) SCFV of Patient V, (C) SCFV of Patient VI

Similar observations were documented in other cases. These findings suggest that patients with identical neglected regions may still exhibit distinct AEAs and SCFVs.

VI. Validation of the SCFV Method Identification Test

To validate the proposed SCFV identification method described in Section 5, an examination was conducted to observe changes in SCFV among patients with USN and the corresponding alterations in their gaze patterns toward visual stimuli. The procedure involved implementing an intervention aimed at improving neglect in patients with USN and identifying neglected areas and the geometric properties of their visual fields both before and after the intervention. If a patient can recognize a visual stimulus without directly looking at it post intervention, it can be inferred that the AEA has expanded. If the AEA identified by the proposed method also shows expansion, the validity of the method can be confirmed.

A. Method

A patient with left USN (Patient I) underwent a 1-month intervention designed to improve neglect symptoms. The patient's neglect was evaluated before and after the intervention using the neglect identification system.

B. Result

Figure 15 shows Patient I's neglect map before and after the intervention. The neglected area before the intervention extended to the right side of the midline, but after the intervention the neglected area decreased to the left side of the midline. The intervention led to an improvement in neglect symptoms.

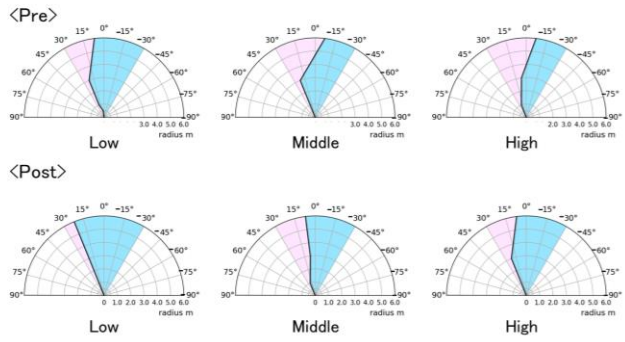

Figure 15. Patient I's pre/post intervention recognition/neglected areas

Figure 16 displays the results of the SCFV identification at a distance of 6m. The ratio of the area of the AEA to the total area of the visual field range was of 0.24 before the intervention and 0.50 after the intervention. Similar expansion of Patient I's AEA was observed at other distances.

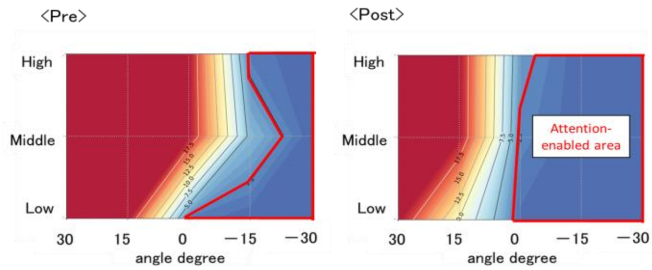

Figure 16. Patient I's pre/post intervention AEA and SCFV

Figure 17 shows Patient I's gaze patterns toward visual stimuli before and after the intervention at a distance of 6m. Before the intervention, Patient I tended to neglect stimuli even when directly gazing at them. After the intervention, however, Patient I was able to recognize visual stimuli at the same locations without directly looking at them, indicating that the AEA had expanded.

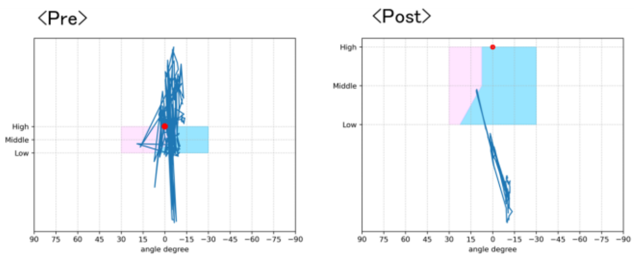

Figure 17. Patient I's pre/post intervention Gaze movement

These results suggest that the proposed SCFV identification method is valid, as evidenced by the expansion of the AEA identified before and after the intervention. Additionally, there was a notable change in the recognition of stimuli, shifting from neglect to recognition, indicating an improvement in neglect symptoms.

VII. Conclusion

The objective of this study was to test the hypothesis that differences in attention to the point of gaze among patients could be defined as SCFV. This hypothesis was validated by examining variations in patients' eye movements toward presented objects using a three-dimensional neglect evaluation system. Additionally, a method for identifying SCFV based on reaction time was developed, focusing on the time taken to recognize objects during evaluation. The identification of SCFV in actual patients revealed significant variations, even among those with identical neglected areas.

While we have offered method for identifying SCFV, further validation of the shape and size of the AEA is needed. It is essential to increase the sample size in future studies to substantiate the accuracy of the AEA's shape and size. Moreover, the threshold for determining the shape of the attentive region, currently normalized to 2.5, has not yet been definitively established. Future research should aim to determine an appropriate threshold through experimental methods.

Traditional neglect evaluations can identify recognition and neglected areas in patients with USN under neck fixation conditions but do not account for SCFV. Consequently, even if two patients exhibit the same neglected areas but have different visual field geometrical characteristics, they might receive identical rehabilitation treatments. This oversight fails to consider the distinct visual field characteristics of each patient. To address this issue, we propose a treatment protocol that considers these differences. By using the proposed method to ascertain each patient's visual field geometric characteristics, it is possible to tailor rehabilitation strategies accordingly. For patients with difficulties related to the AEA's size and shape, a rehabilitation protocol aimed at expanding the AEA can be proposed. In cases where attentional issues within the recognition area are absent, a rehabilitation protocol focused solely on expanding the recognition area may suffice. For instance, in patients with attentional deficits, a rehabilitative approach could involve separately presenting stimuli for gaze and attention. By having the patient fixate on a stimulus to be gazed at while moving a different stimulus to be attended to outside the AEA, the expansion of the AEA can be facilitated. Therefore, by combining conventional and novel intervention techniques tailored to the specific deficits of each patient, it is possible to effectively address neglect symptoms.

Institutional Review Board Statement

This study was conducted in accordance with the guidelines of the Declaration of Helsinki and was approved by the local ethics committee of Waseda University.

Informed Consent Statement

Written informed consent was obtained from all individuals involved in the study. Data Availability Statement: Data are available upon request due to restrictions such as privacy or ethical considerations. The data presented in this study can be obtained from the corresponding author. They are not publicly available because of data privacy regulations.

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Conflicts of Interest

The authors declare no conflict of interest.

Authors Contribution

Akira Koshino and Rikushi Sabu contributed equally to this paper.

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