Effects of an HMD-based Attention System on Head and Eye Movement Strategies of Patients with Spatial Neglect

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Research Article

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Effects of an HMD-based Attention System on Head and Eye Movement Strategies of Patients with Spatial Neglect

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ABSTRACT

Background: Spatial neglect is a visual cognitive impairment that causes patients to ignore the space on the contralateral side of the lesion. Here, we confirmed neglect symptoms using spatial differences, investigated the influence of the attention system, and investigated head and eye movements in patients with spatial neglect using a head-mounted display (HMD).

Methods: We recruited eight participants who had a stroke with right-sided lesions (left-sided neglect) and evaluated their neglect symptoms using the Behavioral Inattention Test and Catherine Bergego Scale Test. Participants performed a cube cancellation task in near and far space, using both an HMD-based normal condition and an attention system.

Results: In near space, no significant differences were observed in the cancellation task performance, but a significant difference was detected in gaze distribution, and a positive correlation was detected in the head and eye movement angles. In far space, a significant difference in the cancellation task performance and gaze distribution, along with a positive correlation among the head and eye movement angles, were observed.
Conclusions: These findings do not significantly refute the results of the cancellation task, but they do suggest that the attentional system may positively influence spatial neglect in terms of head and eye movement strategies.

Keywords: attention, head-mounted display (HMD), spatial neglect, stroke, virtual reality (VR)

1. INTRODUCTION

Spatial neglect is a type of higher brain dysfunction commonly experienced after stroke. It is clinically classified into several types, one of which is visual cognitive impairment that ignores the space on the side opposite to the lesion [1]. Spatial neglect is a factor that delays the improvement of motor and cognitive functions and impedes independence in daily life [2–4]. The prevalence of spatial neglect is reported to be 38% to 60% in the acute phase and approximately 30% in the chronic phase [5]. Even with inpatient occupational therapy interventions, patients with spatial neglect are discharged with a low degree of independence in activities of daily living. Therefore, it is important to identify the symptoms of spatial neglect from an early stage and provide an appropriate corresponding intervention [4].
Spatial neglect can be evaluated using the Behavioral Inattention Test (BIT), which is a paper test [6], and the Catherine Bergego Scale (CBS), which is based on observations of daily life [7,8]. Furthermore, the CBS has a higher evaluation sensitivity than BIT and can detect symptoms of neglect that cannot be ascertained by paper tests alone. This could be due to the need for more focused attention by the patients regarding their surroundings than in paper-and-pencil testing [7]. A recent study demonstrated that eye movement measurement may be effective in evaluating spatial neglect [9] and that the left-right asymmetry of searching patterns as determined by eye movement measurement may complement the results of existing paper tests. A study on head and eye movement strategies in monkeys reported that head and eye movements work cooperatively when the head is not fixed [10]. Coordination between head and eye movements has also been reported in studies on humans [11]. However, the nature of head and eye movement strategies in patients with spatial neglect during exploratory activities is not clear.

Reports of spatial neglect in daily life are controversial regarding the appearance of neglect symptoms owing to differences in spatial distance between studies. Regarding spatial differences, neglect symptoms differ between near and far spaces. Specifically, cases have been reported in which symptoms of neglect are more pronounced in far
space than in near space [12]. Alternatively, there are also studies reporting that neglect symptoms appear only in spaces within a person’s reach and are attenuated in spaces beyond their reach [13,14]. Typical evaluations of neglect symptoms owing to spatial differences have been observed using the line bisection and cancellation tasks. The line bisection task is thought to reflect impairments in visual-spatial perception, while the cancellation task reflects impairments in visuomotor spatial exploration [1]. In the line bisection task, there is a remarkable far space neglect, while neglect is unaffected by differences in spatial distance in the cancellation task [15]. Based on previous evidence, it seems possible to examine neglect symptoms in each spatial area by selecting the appropriate testing methods under different spatial conditions. However, when applying these testing methods clinically, their results may be influenced by visual information, as well as other perceptual information. This limits our understanding of the detailed mechanisms of neglect symptoms.

Various methods have been proposed as interventions for spatial neglect, among which methods involving eye movement training have been reported to be potentially effective [16]. However, it is necessary to examine how to induce eye movement on the neglected side. Recently, virtual reality (VR) applications have been investigated for evaluation and training of unilateral spatial neglect [17–23]. Evaluation of hemispatial neglect
using VR enables evaluation of each subtype of neglect symptoms by controlling the
stimulus conditions, indicating the potential usefulness of training using VR. In
particular, Yasuda et al. [19] clarified the characteristics of neglect symptoms in VR
space while the participant’s head is fixed and are considering its application in training.
In that study, the assessment of spatial neglect status was based on the patient's own
verbal report of the presence or absence of perception. However, verbal reports do not
necessarily reflect the actual perceptual situation; therefore, future studies should aim to
develop a direct measurement method.

We previously investigated the evaluation and training of neglect symptoms owing to
visuospatial cognitive impairment using a head-mounted display (HMD), in which the
patient's movements in a three-dimensional space are synchronized with the HMD
images [24–26]. Previous reports indicate that tasks performed using HMD may capture
symptoms of spatial neglect better than previous clinical assessments [25]. However,
previous evidence indicates a limited ability for HMD tasks used to reflect eye
movements and examine the characteristics of patients’ visual search [26]. In this study,
we modified the previously used evaluation system for spatial neglect to provide a
cancellation task in a space more similar to a real-world environment and created a
system that relies on the patient’s active attention, using visual stimuli. Knobel et al.
[27] developed a cancellation task with motion in near space using an HMD and reported correlations with results from extant tests. The system we developed permits performance tasks in near and far space and can measure head and eye movements during the task.

Therefore, the purpose of this study is to 1) confirm neglect symptoms in spatial distance differences, 2) clarify the influence of the attention system on the visual search of patients with spatial neglect, and 3) clarify the strategy involved in the movement of the head and eyes in these patients.

2. MATERIALS AND METHODS

2.1. Participants

Eight people who had suffered a stroke (two with cerebral hemorrhages and six with cerebral infarctions) participated in the study and provided informed consent for participation. Among them, five were male and three were female with no obvious sex biases. The average age was 72.1 ± 5.4 years, and the average time since ictus was 53 days, range: 19–159 days. All participants had right-sided lesions, had Mini-Mental State Examination (MMSE) scores of 23 or higher, and were right-handed. To evaluate spatial neglect, we conducted the Japanese version of BIT [28] and CBS. BIT can easily
evaluate the symptoms of spatial neglect in a desktop test setting. Alternatively, the CBS
is sensitive in detecting spatial neglect by observing daily behavior and can evaluate
spatial neglect symptoms that cannot be extracted using the BIT [8]. Collaborators
showed neglect symptoms of the left space on either or both the BIT and CBS tests
(Table 1). Although the sample for this study was relatively small, previous studies on
spatial neglect were conducted with similarly sized samples [17,19,22-27].

This research was conducted in accordance with the Ethics Committee of the Research
Center for Advanced Science and Technology, The University of Tokyo (approval
number: 21-232). Written and verbal informed consent was obtained for all study
participants.
2.2. Experimental environment and system

Each participant sat on a chair, wore an HMD (VIVE Pro Eye; HTC Inc. New Taipei City, Taiwan), and held a hand controller in their right hand. This experimental device can measure the spatial coordinate value of the hand controller, the angle of the head, and the angle of the eye-by-eye tracking. The sampling frequency for these data was 50 Hz. The accuracy of eye tracking was 0.5 to 1.1 degrees. The viewing angle of the HMD was 110 degrees, and a three-dimensional space measuring 4 m wide x 4 m high x 5 m deep was projected onto the screen. Changes in the projected image due to

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Table 1. Participants characteristics

<table>
<thead>
<tr>
<th>ID</th>
<th>Sex</th>
<th>Age</th>
<th>Diagnosis</th>
<th>Lesion</th>
<th>Onset</th>
<th>MMSE</th>
<th>BIT</th>
<th>CBS</th>
<th>FIM-M</th>
<th>FIM-C</th>
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<td>MCA, PCA</td>
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<td>24</td>
<td>45</td>
<td>22</td>
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<td>15</td>
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<td>71</td>
<td>hemorrhage</td>
<td>T</td>
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<td>138</td>
<td>2</td>
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<td>MCA</td>
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<td>26</td>
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<td>12</td>
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<td>MCA</td>
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<td>27</td>
<td>141</td>
<td>2</td>
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<td>MCA</td>
<td>19 days</td>
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<td>23</td>
<td>129</td>
<td>2</td>
<td>31</td>
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MCA; middle cerebral artery territory
PCA; posterior cerebral artery territory
T; temporal lebe
MMSE; mini mental state examination
BIT; behavioural inattention test
CBS; Catherine Bergego scale
FIM-M; Functional Independence Measure, (Motor Items)
FIM-C; Functional Independence Measure, (Cognitive Items)
*The lesion was right sided
movements of the head and trunk, as well as movements of the hand controller, were synchronized in the real environment and VR.

Using the HMD, we clarified the symptoms of neglect in each space by asking the participants to perform a task that involved erasing cubes projected in near and far spaces and examined the effect of alerting (via our attention system) on the symptoms of neglect.

In previous studies, the near space was defined as 0.4–0.6 m, which is within arms’ reach range, and the far space was defined as approximately 1.6–3.0 m, beyond arms’ reach [12,15, 29]. However, studies vary in terms of the distance set for far space: e.g., far space by HMD has previously been set at 15 m [19]. In this study, arms’ reach range was defined as the near space, and the maximum spatial distance that could be set with this experimental equipment, 4–5 m, was defined as the far space [29]. Specifically, the cubes in the near space were projected at distances of 0.35 m, 0.45 m, and 0.55 m from the experiment collaborators and were within patients’ reach. In addition, cubes in the far space were projected on concentric circles centered on the head at distances of 4.0 m, 4.3 m, and 4.6 m from the participant. The cubes were positioned at 50 degrees in the frontal and lateral directions and 40 degrees in the vertical direction in both near and far space to unify the search area for visual search (Figure 1).
Figure 1. Display space for cancellation task. The following figures show the positional relationship between the participant and the projected cube in the TOP VIEW: 0.35 m, 0.45 m, and 0.55 m in near space and 4.0 m, 4.3 m, and 4.6 m in far space. A cube in the far space is an extension of a cube projected in the near space.

For each of the near and far spaces, the screen was divided into three regions vertically and horizontally, and cubes were projected at three different depths in each of the nine regions. Nine cubes were projected at a time, and a three-trial cancellation task was performed per spatial condition, with a maximum of 27 cubes projected within both the near and far spaces. The display size of the cube and the method of erasing the cube were slightly different between the near and far spaces. The cubes in the near space measured 5 cm across their side. To erase them, a hand controller was displayed on the screen, and they were erased by superimposing the projected hand controller on each cube for 1 sec. In the far space, each cube measured 20 cm across its side, and a sphere was projected at a distance of 3.8 m from the tip of the hand controller. Participants erased the cube by placing the sphere on top of the cube for 1 sec (Figure 2).
Figure 2. Projection of cubes in different spaces and how to erase cubes. (a) Near space superimposes the projected hand controller on each cube and erases it. (b) Far space superimposes the projected sphere on the cubes and erases it.

In the attention system of this experimental device, an arrow moves from the right edge of the HMD screen to the left edge during the cancellation task (Figure 3). The arrow moves every second, and upon reaching the left edge of the screen, it repeats the movement starting from the right edge of the screen.

Figure 3. Alert system for each space. For both (a) near-space and (b) far-space with alerts, the arrow moved from the right edge to the left edge of the HMD screen during the cancellation task.
2.3. Procedure

Participants started the experiment by sitting on a chair with a backrest or a wheelchair, wearing an HMD, and holding a hand controller in their right hand. When the participants had worn the HMD, they faced forward and calibrated their spatial coordinates. At that time, a therapist fixed the patient's head from behind and restricted head movement during the calibration.

For the cancellation task, after performing a normal condition without alerting (Normal), an alerting condition with an arrow (Alert) was performed. The order of near or far space was randomized for each participant. All experimental participants received a verbal explanation of the cancellation method before the start of the experiment and practiced cancellation in the near and far spaces for approximately 3 minutes each to confirm that they understood the method of performing the task. To ensure that the participants had an opportunity to erase all 27 cubes under a given condition, three trials were conducted for each condition. There was no time limit for any trial, and the experiment proceeded to the next trial upon the participant's voluntary declaration of termination. Head and trunk movements were not restricted during the experiment.

2.3. Analysis
2.3.1. Number of cancellations

The number of cancellations (up to 27) of the cubes projected into space was recorded. For the analysis, the space was divided into left, center, and right, and the number of erased cubes in each were compared for each condition. The maximum number of cancellations of cubes possible in each divided space was nine. The number of cancellations was calculated for each of the four conditions of near space Normal, near space Alert, far space Normal, and far space Alert, and the average value for each condition was determined. The values for the Normal and Alert conditions were compared for the left, center, and right regions in the near and far spaces. Due to the small number of experimental participants, we did not perform a comparative analysis by lesion, course from onset, or symptoms. All statistical analyses were performed using Easy R (EZR), a graphical user interface for R (The R Foundation for Statistical Computing, Vienna, Austria) [30]. Statistical procedures were performed using the Shapiro–Wilk test for normality of values, and homoscedasticity was confirmed by F-test. If normality and homoscedasticity were confirmed, the t-test was performed; otherwise, the Wilcoxon signed-rank test was used. The significance level was set at p < 0.05. For the calculation of the effect size (compute.es package of R), Cohen's d was calculated when normality was confirmed; otherwise, Cliff's Delta was calculated. The
effect size indicates the magnitude of the difference in test results, and Cohen's d can interpret effect sizes >0.2, >0.5, and >0.8 as indicators of small, medium, and large, respectively [31]. Additionally, Cliff's Delta <0.10, <0.33, <0.474, and ≥0.474 can be interpreted as negligible, small, moderate, and large effect sizes, respectively [32].

2.3.2. Gaze distribution

As the gaze distribution varied from the start to the end of each task, we extracted the temporal change from the total value of the angles of the head and eyes. A study on the accuracy of the VIVE's eye tracking reported that accuracy is high at the center of the gaze and decreases with movement to the left/right and up/down, and accuracy was approximately ±30° from the center [33]. In this study, we divided and compared the extracted gaze distribution data into three areas: the center, which has high accuracy, the left side, and the right side. The three regions were defined as 0 degrees along a line extended from each participant's head, with the center range 15 degrees to the left and right, with 15 degrees or more on the right side and -15 degrees or less on the left side (Figure 4). This left and right 15-degree angle is located halfway between the central cube and the adjacent cubes. Therefore, with 0 degrees on the line extending from the head as the standard reference, values exceeding 15 degrees on either side were judged
as exploration into the space of the adjacent cube, and the influence on eye tracking accuracy was minimized. The average value was calculated from the proportion of the gaze distribution in each region obtained for each participant and compared for each of the three regions in the Normal and Alert conditions in the near space and the Normal and Alert conditions in the far space. The statistical analysis performed was similar to that for the analysis of the number of cancellations.

Figure 4. Gaze distribution by analysis areas. Gaze was divided into three regions (left side, center, and right side), and the percentage of gaze distribution per region was calculated.

2.3.3. Relationship between head and eye movement angles

Analysis based on the distribution of gaze cannot examine whether visual search during a task is performed by the head movements, eye movements, or a combination of both. Therefore, we examined the relationship between the angle of head movement and the
angle of eye movement (Figure 5). Using the angle data of the head and eyes extracted during the task, the movement angle was calculated by extracting each angle data point in the horizontal direction from the time when the first cube was erased until the last time a cube was erased. We calculated the amount of displacement of each angle data point of the head and eyes at the time of erasing the cube and each angle data at the time of erasing the next cube.

Figure 5. Head and eye movement angles. The displacement of the horizontal movement angles of the head and eyes was calculated as shown in the red and blue diagrams, respectively.

We examined correlations (Spearman's rank correlation coefficient) for Normal and Alert conditions in the near and far spaces, using the lateral movement angles of the head and eyes for each cancellation of cubes for each of the collaborators. In addition, we performed a test for differences in correlation coefficients for each space (t test
using R’s psych package). For the correlation coefficient values, we used Cohen’s interpretation of 0.1 as small, 0.3 as medium, and 0.5 as large [34].

3. RESULTS

3.1. Number of cancellations

Figure 6 shows the number of cancellations in the near space. For the Normal condition, mean values were $7.63 \pm 2.91$ on the left, $8.50 \pm 1.00$ in the center, and $8.88 \pm 0.33$ on the right. For the Alert condition, mean values were $7.63 \pm 2.96$ on the left, $8.88 \pm 0.33$ in the center, and $8.88 \pm 0.33$ on the right. In a comparison between the Normal and Alert conditions, Wilcoxon signed rank sum test showed no significant difference for the left side ($p = 1.000$), center ($p = 0.371$), and right side ($p = 1.000$). Conversely, in terms of effect size, Cliff’s Delta were 0, 0.28, and 0 for the left, center, and right, respectively, with a tendency to show a weaker effect in the center space.
Figure 6. The number of cancellations in the near space. A comparison of the number of cancellations between normal and alert conditions is shown for each area: (a) left side, (b) center, and (c) right side. A weaker effect is only observed in the center (b).

Figure 7 shows the number of cancellations in far space. The Normal condition had an average of 4.50 ± 3.24 on the left, 6.50 ± 1.50 in the center, and 6.88 ± 1.54 on the right. Moreover, the Alert condition had an average of 6.50 ± 2.50 on the left, 7.38 ± 1.22 in the center, and 7.63 ± 1.22 on the right. A t-test compared the Normal and Alert conditions (the left side [p = 0.025], the center [p = 0.111], and the right side [p = 0.197]) and showed a significant difference in the left side space. In addition, the effect size tended to be large in all spaces. Cohen's d was 0.69, 0.64, and 0.54 for the left side, center, and right side, respectively.
Figure 7. The number of cancellations in the far space. A comparison of the number of cancellations between normal and alert conditions is shown for each area: (a) left side, (b) center, and (c) right side. The effect size tended to be large in all the spaces.

3.2. Distribution of gaze

Figure 8 shows the distribution of gaze in the near space. The Normal condition had an average of $20.2 \pm 8.8\%$ on the left, $36.3 \pm 12.6\%$ in the center, and $43.6 \pm 17.2\%$ on the right. Moreover, the Alert condition had an average of $31.1 \pm 10.6\%$ on the left, $41.8 \pm 14.2\%$ in the center, and $27.1 \pm 9.2\%$ on the right. In the comparison between the Normal and Alert conditions, the left ($p = 0.00391$) and the right ($p = 0.0778$) sides were determined by a t-test. However, the center ($p = 0.844$) was determined by the Wilcoxon signed rank sum test, and a significant difference was observed on the left side. Cohen's $d$ indicated a large effect size on the left (1.13) and right (1.34) sides, and Cliff's Delta showed a tendency for a weak effect size in the center (0.23).
Figure 8. The distribution of gaze in the near space. A comparison of the distribution of gaze between normal and alert is shown for each area: (a) left side, (b) center, and (c) right side. A significant difference was observed on the left side (a). The effect size tended to be large on the left (a) and the right (c) sides.

Figure 9 shows the distribution of gaze in far space. The Normal condition had an average of $15.6 \pm 10.2\%$ on the left, $47.8 \pm 13.7\%$ in the center, and $36.6 \pm 11.7\%$ on the right. Moreover, the Alert condition had an average of $31.6 \pm 9.1\%$ on the left, $41.3 \pm 8.9\%$ in the center, and $27.1 \pm 9.5\%$ on the right. In the comparison between the Normal and Alert conditions, the left side ($p = 0.0187$) and center ($p = 0.0642$) were determined via a t-test. However, the right side ($p = 0.0547$) was determined via the Wilcoxon signed rank sum test; additionally, a significant difference was observed in the left space. Additionally, a trend toward moderate effect sizes was observed in the right space (0.47) based on Cliff’s Delta. On the contrary, moderate and large effect sizes were evident in the center (0.57) and left side (1.66), respectively, based on Cohen's d.
Figure 9. The distribution of gaze in the far space. A comparison of the distribution of gaze between normal and alert is shown for each area: (a) left side, (b) center, and (c) right side. A significant difference was observed on the left side (a). The effect size tended to be larger in the left side (a).

3.3. Relationship between head and eye movement angles

Figure 10 shows the relationship between the movement angles of the head and eyes in the near space. The results for the Normal and Alert conditions were $r = 0.129$, $p = 0.0757$ and $r = 0.412$, $p = 1.82 \times 10^{-9}$, respectively. In the Normal condition, no significant difference was observed in the non-correlation test, and no correlation was observed. However, in the Alert condition, a moderate positive correlation was observed. In addition, the difference in the correlation coefficient between the Normal and Alert conditions was $z = 3$, $p = 0$. 
Figure 10. The movement angles of the head and eyes in the near space. (a) In the Normal condition, no correlation was observed in the relationship between head and eye movement angles. (b) In the Alert condition, a moderate positive correlation was observed.

Figure 11 shows the relationship between the movement angles of the head and eyes in far space. The results for the Normal and Alert conditions were $r = 0.348$, $p = 4.95 \times 10^{-5}$ and $r = 0.644$, $p = 0$, respectively. Furthermore, a moderate positive correlation was observed in the Normal condition. However, in the Alert condition, a strong positive correlation was observed. Moreover, the difference in the correlation coefficient between the Normal and Alert conditions was $z = 3.4$, $p = 0$.

Figure 11. The movement angles of the head and eyes in the far space. (a) A moderate positive correlation was observed under normal conditions. (b) Under the alert condition, a strong positive correlation was observed.
4. DISCUSSION

In this study, we confirmed the symptoms of neglect owing to spatial differences through a cancellation task using an HMD and examined how an attention system would affect the symptoms of spatial neglect. Regarding the effects of spatial neglect on symptoms, we investigated the number of cancellations in each space, which captures direct changes in the task, and the distribution of gazes, which determines the bias of visual search within the space for performing the task. Furthermore, we examined the relationship between the head and the eyes, which is a feature of the strategy in visual search. The main finding of this study was that the peripheral number tended to increase considerably in the left region of the far space when alerting was used. In addition, the proportion of gazing at the left region of the near and far spaces markedly increased. Furthermore, in relation to the lateral movement angle of the head and eyes, a moderate positive correlation was observed in the near and far spaces, and a marked difference was also observed in the difference in the correlation coefficient. This suggests that the use of alerting during tasks within the HMD may influence visual search in the left area and may affect the strategy of visual search itself.

4.1. Number of cancellations
Comparison of the number of cancellations between the Normal and Alert conditions in the near space revealed no significant difference on the left side, center, or right side. However, when viewed as an effect size in the center, there was a trend toward a weak difference and the possibility of an increase in the number of cancellations owing to the use of caution cannot be denied. Furthermore, it is possible that because the neglect symptoms in the near space were mild, it was difficult to produce a difference that would have been sufficient to detect the effects of attention.

Comparison of the number of cancellations between the Normal and Alert conditions in the far space revealed a notable increase in the number of cancellations on the left side and in the center. Furthermore, the effect sizes tended to show moderate differences in all spaces. These results indicate that in the far space, alerting may improve performance on the extinction task.

Compared to the far space, neglect symptoms were milder in the near space, which appears to be similar to a previous report showing no neglect symptoms in the near space [14]. Normally, extinction tasks are characterized by the integration of perception and movement as part of task performance, which involves actual movement after visual perception, and it has been pointed out that the movement is based on egocentric references and may not be affected by distance [15]. Nevertheless, the results of the
Normal and Alert conditions differed in each space and seemed to be consistent with the hypothesis that states that dissociations are caused by the differences in the required brain activity in different spaces [14].

In both the near and far spaces, there was a tendency toward a certain difference in the effect size in terms of the number of cancellations when alerting was used. This suggests that alerting may have some influence on visual search. By comparing the number of cancellations, it is possible to elucidate the nature of neglect symptoms. However, it is necessary to examine the strategic factors that facilitate cancellations through other analyses.

4.2. Gaze distribution

Measuring eye movements in patients with spatial neglect is a useful evaluation tool that complements the existing paper-and-pen test; furthermore, eye movement measurements help in gaining insight into spatial working memory [9,35]. Here, after examining the ratio of line-of-sight distribution in the near space, the distribution of gaze was greater in the center and on the right side than on the left side in the Normal condition. In the Alert condition, as the gaze distribution on the right side decreased, the distribution of gaze on the center and left side increased. Furthermore, when compared
to the Normal condition, there was a significant increase in the proportion of gaze
distribution on the left side. In addition, the effect size tended to display a strong
difference between the right and left sides. This indicates the possibility that the gaze is
led from the right side to the left side, owing to the Alert condition.

In the far space, in the Normal condition, the distribution of gazes was greater in the
center and on the right side than on the left side, as in the near space. During the
attention task, the left gaze distribution significantly increased while the right gaze
distribution decreased. In addition, the effect size tended to show a strong difference on
the left side and a moderate difference in the center and on the right side. This suggests
the possibility that the gaze was led from the right side to the left side owing to the Alert
condition, even in the far space.

The characteristics of the alerting used in this study seem to be related to the change in
the distribution of gaze from the right side to the left side when attention was used,
regardless of whether it was in the near or far spaces. In this attention system, an arrow
image displayed on the HMD screen continuously moves from the right side to the left
side, and following the arrow image guides attention to the left side. Visual scanning
training and smooth eye movements have been reported as effective interventions for
spatial neglect [16, 36]. Our attention system followed the arrow image from the right
side to left side, resulting in a similar effect to left visual scanning method using smooth eye movements.

Analysis based on the ratio of gaze distribution showed that it is possible to capture neglect symptoms by measuring eye movements, as in past reports, and that it is possible to capture behavioral changes on a perceptual level via the alerting condition [9,25,33].

4.3. Relation between head and eye movement

When measuring eye movements, the head must be immobilized, and the standard objects of analysis are ocular fixation and saccades [37]. However, previous findings on the relationship between the head and eyes indicate that when the direction of the gaze is fixed, head movement precedes eye movement, and that head and eye movements are closely linked [11]. Furthermore, a study investigating the effects of aging on the relationship between the head and eyes reported that the deviation of the head becomes larger than that of the eyes with aging [38]. However, the relationship between the head and eyes in spatial neglect has not been investigated so far. Hence, the results of our study may elucidate the visual search strategy of patients with spatial neglect. This assessment may be necessary to understand the symptoms of spatial neglect, since
actual exploratory activity involves not only eye movements, but also coordinated head and eye exploration.

The current findings indicate no correlation between the head and eye movements in the near space, in the Normal condition. However, in the Alert condition, a correlation was observed, resulting in a significant difference in correlation coefficients. The fact that the correlation between the head and eyes was not observed in the Normal condition indicates that the motor strategy of head and eye movement in visual search in patients with spatial neglect may be highly individualized. This seems to be influenced by perceptual strategies during information processing. However, rehabilitation for spatial neglect is known to draw attention to the left side of the space by not only eye movements but also rotational movements of the head and trunk [39,40]. This suggests that the perceptual strategy for exploring left-sided space may require not only eye movements but also coordination between the eyes and other body parts, and our results suggest that patients with spatial neglect may have impaired perceptual strategy for exploring space.

In the far space, a positive correlation was observed for both Normal and Alert conditions, wherein there was a strong trend toward a positive correlation for the Alert condition; additionally, a difference was observed for the differences in the correlation
coefficients. This suggests that cueing attention during a peripheral task may promote a coordinated action between the head and eyes.

The correlation between the head and eyes in the Normal condition differed between the near and far spaces. Are different perceptual strategies used depending on differences in spatial conditions, are perceptual strategies unique to each patient, or are perceptual strategies themselves impaired when patients suffer from this condition? We cannot yet make a clear distinction between these possibilities based on the present findings alone. However, in the Alert condition, both the near and far spaces showed a positive correlation, suggesting that it may have a better influence on perceptual strategies during the extinction task.

4.4. Limitations

This study has some limitations. Among the participants, there was a variation in the number of days since the onset of symptoms, which may have caused differences in the improvements of their neglect symptoms. As a result, there is a possibility that the examination of the influence of the attention system on their visual search may have been affected. Additionally, because only a small number of participants were included, comparisons between the lesions were not possible, making it difficult to examine
differences in their brain activity and how they might have affected the results.

Furthermore, the present analysis of gaze distribution and head and eye movement strategies was limited to the horizontal plane.

5. CONCLUSIONS

In this study, we examined the symptoms of neglect in different spaces via the cancellation task using HMD, and accordingly, shed light on the possibility of extracting the characteristics of perceptual strategies in spatial exploration. In addition, our findings suggest that attention systems may have a positive impact on spatial neglect. These systems not only draw attention to the neglected space but also stimulate the perceptual strategy itself to explore and may change the strategy behind head and eye movements for patients with spatial neglect.

Declarations

Ethics approval and consent to participate

This research was conducted in accordance with the Ethics Committee of the Research Center for Advanced Science and Technology, The University of Tokyo (approval number: 21-232).
Consent for publication

Written and verbal informed consent was obtained for all study participants.

Availability of data and materials

Data is stored on a password-protected computer at Hokkaido University of Science.

Competing interests

The authors declare that they have no competing interests.

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Author contributions

AK performed the design of this study, acquisition and analysis of data and drafting the manuscript. NK made major contributions to the design of this study, acquisition and analysis of data. TT and TM were involved in conception and design of the study, interpretation of the data and revision of the manuscript for important intellectual content. Each of the authors has read and concurs with the content in the final manuscript.

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