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Original Article

Assessment of visual space recognition of patients with unilateral spatial neglect and visual field defects using a head mounted display system

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Abstract. [Purpose] The purpose of this study was the development of a method for presenting diverse visual information and assessing visual space recognition using a new head mounted display (HMD) system. [Subjects] Eight patients: four with unilateral spatial neglect (USN) and four with visual field defects (VFD). [Methods] A test sheet was placed on a desk, and its image was projected on the display of the HMD. Then, space recognition assessment was conducted using a cancellation test and motion analysis of the eyeballs and head under four conditions with images reduced in size and shifted. [Results] Leftward visual search was dominant in VFD patients, while rightward visual search was dominant in USN patients. The angular velocity of leftward eye movement during visual search of the right sheet decreased in both patient types. Motion analysis revealed a tendency of VFD patients to rotate the head in the affected direction under the left reduction condition, whereas USN patients rotated it in the opposite direction of the neglect. [Conclusion] A new HMD system was developed for presenting diverse visual information and assessing visual space recognition which identified the differences in the disturbance of visual space recognition of VFD and USN patients were indicated.

Key words: Unilateral spatial neglect, Visual field defects, Visual space recognition

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INTRODUCTION

Typical disturbances of visual space recognition include unilateral spatial neglect (USN) and visual field defects (VFD). However many aspects of these disorders remain unknown, such as their differences.

It is believed that VFD is present in about 40% of patients with cerebrovascular diseases, and that it is spontaneously recovered in 50–60% of them[1)]. Principal lesion locations include the lateral geniculate body and temporal lobe[2)], and occipital lobe[3)], where homonymous hemianopsia reportedly occurs. A recent report has described the efficacy of rehabilitation for VFD[4)], indicating the efficacy of the compensation method by eye movement. A trend of capturing a visual object in the central visual field to acquire accurate information has also been described[5)]. VFD patients try to obtain visual information by concentrating on a field area that remains in the central visual field. Accordingly, it is necessary for them to acquire information by eye movement to capture an object in an unaffected visual field and head rotation toward the affected visual

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field. These actions are usually designated as visual search.

Several assessment methods of visual search reportedly exist, and include a method of measuring the search range for a designated target with the head fixed, and a method of ascertaining the search time and the number of correct answers in a search for a geometric configuration[6, 7]. Moreover, accurate comprehension of pathology requires modification of a head movement state and the range of instruction without body constraint as in activities of daily living (ADL). However, few reports have described the measurement or analysis of eye movement at the time of presenting such diverse visual information.

Disturbances of space recognition following USN include disorders such as colliding with people or objects during activities of daily living or wheelchair accidents caused by failure to operate the brake on the left-hand side. Accordingly, supervision by a caregiver is often indispensable, even after recovery of motor function by rehabilitation, so USN it is a great hindrance to the independence of people with disability[8]. The onset of USN is mostly observed in patients with cerebrovascular diseases in the right hemisphere from the acute stage to chronic stages[9]. It is less frequent in patients with cerebrovascular diseases in the left hemisphere, persisting only slightly until the chronic stage[10].

Test methods for USN include a cancellation test, copy test, drawing test, and line bisection test. The behavioral inattention test (BIT) normalizes these, including laboratory tests imitating daily living scenes[11]. The Catherine Bergego scale (CBS) is an assessment method for unilateral spatial neglect symptoms in ADL, for which therapists evaluate activities of 10 types in a real situations by observation. USN is observed even in cases where USN is not observed by desk checking according to CBS[12], so the CBS is regarded as useful as a USN assessment method in ADL.

Hillis revealed differences in focal sites due to neglect related to the deviation of egocentric and allocentric standards using magnetic resonance imaging (MRI)[13, 14]. Consequently, it is commonly considered that methods for recognizing exterior space include a reference frame centering on an individual's own body (egocentric reference frame) and that centering on an object (allocentric reference frame). USN is classified roughly into the following two types: egocentric neglect, in which the viewer-centered unilateral space is neglected centering on the truncus, head, and retina; and allocentric neglect, in which the unilateral space of an object is neglected centering on the object itself in the exterior space, irrespective of the relation to the individual's own body position.

Jeffrey et al. investigated the relation between six BIT subtests and damaged areas, and examined the relevance between egocentric and allocentric neglect. They reported that egocentric neglect is related to the results of the star, letter, and line cancellation tasks and damaged areas in the frontal and parietal lobes, whereas allocentric neglect is related to the results of the line bisection, copying, and drawing tasks, and damaged areas in the temporal and parietal lobes[15]. These results suggest that USN might exhibit various symptoms under the effect of different inputs. Accordingly, it is necessary to carry out assessment and examination from multiple and different viewpoints for accurate comprehension and analysis of USN[16, 17].

The aim of this study was to evaluate a new head mounted display (HMD) system that has been devised for quantitatively assessing the visual recognition of patients with cerebrovascular diseases[18, 19]. USN symptoms not disclosed by the ordinary line cancellation test were found by the HMD system. Eyes and head movement analysis were also added to the HMD system[20, 21].

Various reports have described the assessment of the eye movement of left USN patients[22–24]. However, few studies have analyzed impairment of the visual field in VFD and USN without body constraint in relation to ADL. The differences between the visual problems of VFD and USN have not been clarified under diverse visual conditions during the simultaneous measurement of movement of the eye, head and trunk. Therefore, the purposes of this study were to assess the eye movements of USN and VFD patients and to clarify the characteristics of the disturbance of spatial recognition.

SUBJECTS AND METHODS

A total of eight subjects participated: four USN patients and four VFD patients (Table 1). The USN patients had right hemisphere damage verified by MRI. Neglect was assessed using the CBS, which is reported to be valid and reliable as an assessment of USN symptoms in ADL[12]. It should be noted that patients unable to remain in a seated position in a wheelchair or chair, with impaired vision, or remarkable dementia as determined by a MMSE score of 20 or less were beyond the scope of this study. Informed consent was obtained from all of the subjects prior to their inclusion in the study. This study received the approval of the Ethics Committee of the Graduate School of Information Science and Technology of Hokkaido University (2010-03).

The line cancellation test was conducted in accordance with the "normal inspection" of the BIT Japan version. For this analysis, the test sheet of the line cancellation test was divided into a left and right side except four lines in the center. Then the percentages of correct answers of the number of lines cancelled were determined on each side. The test was performed under all conditions for comparison of the results (Fig. 1).

The HMD system captured the image of the test sheet with an overhead camera and displayed the image on the liquid crystal display (LCD) inside the HMD unit. The HMD system control unit can reduce the image size or shift the image on the LCD. The HMD system can produce images for a patient to view the test sheet easily, or not to view it, to evaluate the severity of visual deficit.

Since the image is viewed in the HMD, the image does not move when the subject's head moves, thereby providing an environment which requires visual search by eye movement to carry out the line cancellation test.

For this study, two miniature CMOS cameras were installed in the HMD unit. This enabled us to record the eye movement of each eye. During the examination, the head and trunk movements were recorded by a digital video camera and the video image was saved synchronous with the eye movement using a monitor splitter. When the subject fixed his/her eye on the center of the test sheet, the positions of the eye, head, and trunk were used as the basic reference position for analyzing their movements (Fig. 2).

The recorded eye movements were analyzed using motion analysis software (Frame-DIAS IV, DKH Inc., Tokyo, Japan). In the analysis, the center position (X, Y) of the eye was identified using the ellipse of the pupil obtained in the image processing binarization of the eye image. Our experiment evaluated the eye position at a sampling frequency of 20 Hz.

When a subject's gaze was fixed on the center of the test sheet, the eye position was analyzed and was used as the reference position. Then, the frequency ratio of the right view to the left view during the test was determined. The frequency distribution of the eye position was determined using the right and left views according to the area of the right and the left regions in the histogram of the eye movement angle. Additionally, the velocity of the angular movement from the angular positions of the eye was calculated at the rate of 1/20 s. This angular velocity of the eye movement was evaluated in the line cancellation test. The difference between the right and the left side sheets was analyzed. Rapid eye movements were excluded from the measured angular velocity data, as in previous studies, data faster than 100 deg/sec were eliminated.

For each condition, with either the right or left side of a test sheet blanked, the present study conducted a two-way analysis of variance with multiple comparisons and Bonferroni correction to determine the significance of differences among the visual presentation conditions in the transverse direction of eye movement and the differences in the angular velocity of eye movement in the transverse direction.

For the tests, subjects sat on a chair and a test sheet was placed on a desk with its midline aligned with that of the subject body. All the tasks were conducted with no restriction on the test time. First, the subject performed the line cancellation test, a commonly performed clinical test, without the HMD. To prepare the HMD, the examiner wore the HMD unit, and adjusted the CMOS camera so that the image of the right eye appeared in the center of the monitor display. Then, the subject wore the HMD unit and the measurement started. After instructing a subject to fix the eyes on the center of the test sheet, video

Table 1. Physical and clinical characteristics of patients with unilateral spatial neglect and visual field defects

Patient	Gender	Age	Aetiology	Lesion location	VFD	Days since onset	MMSE	CBS
VFD1	M	60	Tumour	parieto-occipital	yes	353 d	28	7
VFD2	F	43	Infarction	occipital, cerebellum	yes	286 d	30	3
VFD3	M	36	Infarction	occipital	yes	75 d	30	3
VFD4	M	54	Infarction	putamen	yes	13 y	30	7
USN1	F	26	Hemorrhage	temporo-parietal	no	164 d	25	8
USN2	M	79	Infarction	fronto-parietal	no	86 d	27	9
USN3	M	78	Hemorrhage	putamen	no	37 d	21	8
USN4	M	58	Infarction	front-parietal	no	35 d	27	8

VFD: visual field defects, USN: unilateral spatial neglect, y: year, d: days, CBS: Catherine Bergego scale

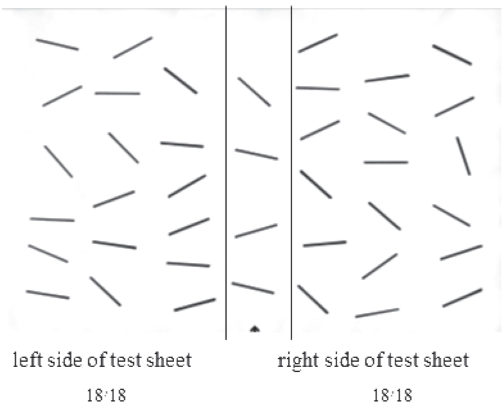

Fig. 1. Analysis method of the line cancellation test

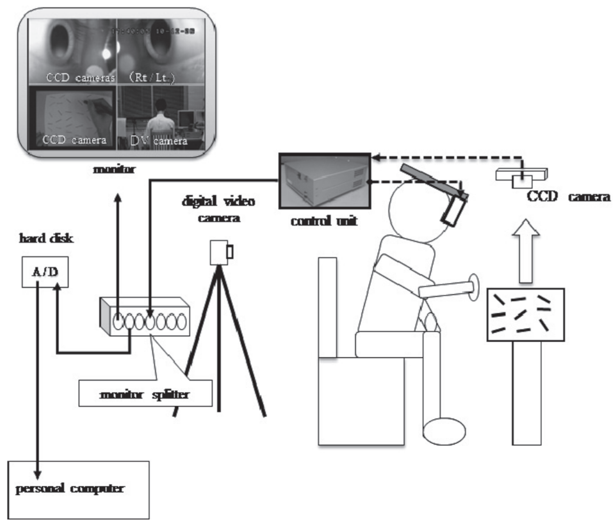

Fig. 2. Experimental apparatus

images of the eye movement were recorded during the examination. The subject performed the line cancellation test using the HMD under the following four conditions: no reduction in the test sheet image, center reduction (80% reduction toward the center of the LCD), and right and left reductions (80% reduction toward the right and left end of the LCD). The subjects performed these tests in that order.

RESULTS

The correct answer rate of VFD patients showed no decline for any condition of the right and left sheets. The eyeball position was higher on the left-hand side under the conditions of no reduction, center reduction, and left reduction of an image on a test sheet, but higher on the right-hand side under the right reduction condition.

USN patients had a correct answer score of 100% for in the left sheet in the common clinical test, although it dropped to 40% under the no-reduction condition of the HMD, 42% under center/right reduction, and 38% under left reduction. In the right sheet, it was 98% in the common clinical test, and declined to 63% under the no-reduction and center reduction conditions, 59% under right reduction, and 61% under left reduction. Therefore, a reduction in the percentage of correct answers for the left sheet was observed in comparison to the right sheet. The eyeball position deviated to the right under all the conditions, and right deviation was especially greater under the center and right reduction conditions. The ratio of the left sheet increased under the left reduction condition.

The angular velocity of eye movement of the VFD patients was significantly faster in leftward eye movement under the right reduction condition for the left sheet, but was not significantly different under the other conditions, even though rightward eye movement was faster for the right sheet (Table 2). The angular velocity of leftward eye movement was faster under the right reduction condition than under the no-reduction condition for the left sheet, even though it was slower under center and left reduction than under no-reduction the right sheet.

The angular velocity of eye movement of the USN patients showed no significant difference according to the direction of eye movement under any condition for the left sheet. However, that of leftward eye movement under the left reduction condition was the fastest. The angular velocity of rightward eye movement increased for the right sheet (Table 2). Moreover, for the right sheet, the angular velocity of leftward eye movement under the center and right reduction conditions was faster than under the no-reduction condition, and slower under left reduction than under center reduction.

Patients VFD1,2 tended to rotate the head leftward, and especially VFD2 shifted the trunk to the left-hand side; patients VFD3,4 did not move the head and trunk. In contrast to the VFD patients, USN patients tended to rotate the head rightward, except for USN2. Patient USN3 did not clearly move the head or trunk. The head and trunk movements of patient USN4 showed no association with eye movement (Table 3).

DISCUSSION

The line cancellation test revealed the HMD did not influence the visual field conditions, according to the line cancellation rate of the VFD patients, even though the percentage of correct answers was lower when USN patients were wearing the HMD. The USN patients in this laboratory test presented left spatial neglect in the everyday life according to the CBS score. A new assessment and training for USN with use of a HMD was proposed by Tanaka et al[19–21]. There are a few reasons for the decline in the line cancellation rate for the right sheet of the VFD and USN patients. One reason is that, because all subjects were right-handed, attention deviated rightward. As they cleared a cancellation test from the right-hand side, their own hand shown on the monitor of the HMD hid lines on the right sheet. Reinhart et al. studied neglect dyslexia in which

Table 2. Mean angular velocity of eye movement under each condition

		Direction of eye movement over the left sheet (deg/s)			Direction of eye movement over the right sheet (deg/s)		
		left direction (SD)	right direction (SD)		left direction (SD)	right direction (SD)	
VFD (n=4)	no reduction	3.9 (6.0)	4.1 (7.2)		4.4 (6.4)	5.2 (8.0)	**
	center reduction	3.5 (5.1)	3.8 (5.7)		3.9 (4.8)	5.3 (6.6)	
	right reduction	4.2 (7.4)	3.9 (6.5)	*	4.3 (6.3)	5.2 (8.5)	**
	left reduction	3.4 (5.2)	3.9 (5.9)		3.8 (5.2)	4.5 (7.1)	*
USN (n=4)	no reduction	5.1 (7.7)	4.6 (7.0)		4.1 (7.1)	6.1 (10.6)	**
	center reduction	4.7 (5.2)	4.1 (6.3)		4.6 (7.5)	6.3 (10.1)	**
	right reduction	3.5 (5.5)	3.6 (5.4)		4.5 (7.1)	5.9 (9.4)	**
	left reduction	5.5 (7.4)	5.3 (7.1)		4.1 (6.6)	5.7 (9.5)	**

**p<0.01, *p<0.05.
VFD: visual field defects, USN: unilateral spatial neglect

the left half of characters or words tends to be overlooked, and reported that manual head rotation in the direction of neglect reduced omission of the left parts of texts, but no such effect was found for words[25)]. Furthermore, Niemeier et al. reported that a frame provided for a search of lines enhanced the gradient of attention, tending not leftward but rightward therein for USN patients[26)]. These results suggest that observing an assessment sheet using an HMD specified the range of attention and diverted attention rightward. The percentage of correct answers for the left sheet increased under the center reduction and right reduction conditions, compared with the no-reduction condition, although it dropped under the left reduction condition. This result is considered to have occurred because the left sheet was shifted to the right-hand side of the screen under the center reduction and right reduction conditions, compared with the no-reduction condition. In contrast, it is our presumption that the percentage of correct answers decreased, because the left sheet was shifted to the left-hand side under the left reduction condition.

The eyeball position of the VFD patients tended to stay over the left sheet under the no-reduction, center reduction, and left reduction conditions, and over the right sheet under only the right reduction condition, probably because of the left reduction condition, assessment sheets tended to be presented on the side of visual field defects, and because compensation by eye movement was enhanced by visual search. Therefore, the ratio of the left-hand side might be increased. In addition, the ratio of the right-hand side might be increased so that the assessment sheets tended to be presented in an unaffected visual field under the right reduction condition. The eyeball position of USN patients deviated rightward under all the conditions: right deviation increased under the center and right reduction conditions, and declined under the left reduction condition. Karnath et al. measured the eye movements of USN patients in darkness where no object was apparent, and reported deviation of visual search to the ipsilesional side[27)]. They also reported that VFD patients moved the visual axis to the left end with visual field defects and conducted bisection, while USN patients did not search for the left end, but performed bisection in a position deviated toward the right-hand side, in an examination of the visual search in the line bisection test[28)]. The eye movement of the USN patients also deviated rightward in this study and leftward for the VFD patients. It is our assumption that this system, in which an image taken with a camera fixed overhead is projected on HMD, implements conditions close to object center coordinates, as well as the effect of the environment where the position of an image remains unshifted irrespective of head motion.

The angular velocity of rightward eye movement of the VFD and USN patients was faster over the right sheet, However, there was no difference in right and left angular velocities of eye movement of the VFD patients over the left sheet, except under the right reduction condition. A similar study of visual spatial attention compared reaction times and found that reaction to a stimulus in the right visual field of USN patients was faster than that of healthy persons by comparison of reaction time[29)]. Moreover, it is our belief that a key stimulus is located on the right-hand side of USN patients in a target stimulus detection task, so that the reaction time is delayed by hundreds of milliseconds or more when a target stimulus occurs in the affected left-hand side compared with a key stimulus on the left-hand side[30)]. It is our conjecture that the eye movement at the time of turning attention leftward was affected, because the key stimulus was on the right-hand side during the cancellation task on the right sheet in this study. When both VFD and USN patients turn attention toward the right side, it is difficult for them to switch attention to the left side from the right side. The angular velocity of leftward eye movement of VFD patients over the right sheet was slower under the no-reduction condition than under either the center or left reduction conditions, although it was faster center and right reduction than no-reduction, and slower under left reduction than under center reduction for USN patients. These results indicate that the eyeball position of each condition affects the angular velocity of leftward eye movement. It is our opinion that VFD patients have little need to move the eyeball fast leftward because their eyeball position is originally deviated leftward. However, that when USN patients are required to move the eyeball leftward fast the eyeball

Table 3. Motion analysis

	head and trunk movement				eye movement			
	no reduction	center reduction	right reduction	left reduction	no reduction	center reduction	right reduction	left reduction
VFD1	←	←	←	←	←	←	←	←
VFD2	←	←	=	←	←	←	←	←
VFD3	=	=	=	=	←	→	→	←
VFD4	=	=	=	←	←	←	→	←
USN1	←	←	←	←	←	←	→	←
USN2	→	→	→	→	→	→	→	→
USN3	=	=	=	=	→	→	→	→
USN4	=	=	→	→	←	→	→	←

Right (→) and left (←) arrows indicate directions of head rotation and eye movement
VFD2 patient showed trunk shift and no head rotation
Equal sign (=) indicates no change in movement
VFD: left visual field defect, USN: unilateral spatial neglect

position is deviated rightward. The angular velocity of eye movement under the left reduction condition was slow over the right sheet but the fastest over the left sheet. This reflects the possibility that presentation of diverse visual information is applicable for the training of rapid eyeball movements in an affected direction and the space of neglect.

Motion analysis of eye movement and head motion revealed the tendency of VFD patients rotate the head in the affected direction under the left reduction condition. Moreover, a decline of speed was observed in the angular velocity of leftward eyeball movement under the left reduction condition, so compensation the head or trunk increased. Patient VFD2 had the smallest visual field. Therefore, VFD2 shifted the trunk to the impaired view to compensate for head movement. The eye movement of USN patients in the acute stage has been reported to deviate rightward and deviation of head motion in severe disorders[24, 31]. Patient USN2 had severe USN. Patients in this study showed a tendency of rightward head rotation. It is our belief that the present HMD system created the environmental conditions which draw attention to the right. However, USN1 rotated the head to the left under all conditions as well as leftward eye movement. Consequently, these results suggest that attention can be shifted leftward in the chronic stage, even under an environment encouraging rightward deviation. As described above, this study demonstrated the importance and usefulness of assessment under an environment close to the ADL of daily living with unconstrained motion of the head or trunk by presentation of various visual information.

A systematic review of for USN reported that visual scanning training (VST), trunk rotation (TR) or repeated neck muscle vibrations (NMV), video feedback training, and prism adaptation (PA) can be recommended for the rehabilitation of patients with left neglect[32]. Recently, several studies of rTMS and tDCS have also been published[33–35]. However, these studies did not indicate a long-term functional improvement of visual spatial impairment.

A new training using various visual stimuli presented by the HMD system will be developed to adjust for to the characteristics of the eye and head movements of patients with spatial cognitive impairment.

The new HMD system might be able to present diverse visual information and to evaluate the objective disturbance of visual space recognition. Furthermore, the present study has elucidated differences in the disturbance of visual space recognition of VFD and USN patients by the analysis of head motion and eye movement using the HMD system.

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