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Effects of mental rotation on acalculia: Differences in the direction of mental rotation account for the differing characteristics of acalculia induced by right and left hemispheric brain injury

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Effects of mental rotation on acalculia: Differences in the direction of mental rotation account for the differing characteristics of acalculia induced by right and left hemispheric brain injury

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We observed a 59-year-old right-handed man with an infarction in his right-middle cerebral artery that included the parietal lobe, who abnormally manipulated mental images in the horizontal direction, resulting in calculation disturbances. Three years later, the patient suffered an infarction in the left parietal lobe and displayed abnormalities during the creation of mental images; i.e., he rotated them in the vertical direction, which again resulted in calculation disturbances. These mental imagery disturbances might indicate that a common acalculia mechanism exists between the right and left hemispheres.

Keywords: Acalculia; Brain damage; Hemispheric differences; Mental rotation disturbance.

Hécaen (1962) classified anarithmetia into three subtypes: (I) spatial anarithmetia, (II) aphasic anarithmetia, and (III) acalculia. Right hemispheric injury can lead to anarithmetia due to unilateral hemispatial neglect and other conditions (Hécaen, Angelergues, & Houllier, 1961). Left hemispheric injury can cause aphasia, which is often accompanied by anarithmetia, regardless of the type of aphasia (Rosselli & Ardila, 1989). As for acalculia, Takayama, Sugishita, Akiguchi, and Kimura (1994) reported three cases of pure acalculia caused by injury to the region surrounding the left intraparietal sulcus. Moreover,

this part of the brain has been shown to be responsible for calculation function in normal subjects by neuroimaging analyses (Gruber, Indefrey, Steinmetz, & Kleinschmidt, 2001; Menon, Rivera, White, Glover, & Reiss, 2001).

Acalculia caused by right hemispheric lesions is generally considered to be less severe than that caused by left hemispheric lesions (Jackson & Warrington, 1996). This has led to the hypothesis that the two hemispheres perform language and calculation functions in a dissociated manner or that one hemisphere is responsible for both (Semenza et al., 2006), which might indicate that a common

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acalculia mechanism is shared by the right and left hemispheres. Although many studies have reported that acalculia is caused by spatial disturbances in patients with right hemispheric lesions, this is not true in all cases of acalculia involving right hemispheric lesions (Basso, Burgis, & Caporali, 2000).

As described earlier, anarithmetia is a syndrome with heterogeneous mechanisms that can be caused by left or right hemispheric injury. However, three important questions remain regarding its causative mechanisms:

- (1) It has been shown that lesions located posterior to either central gyrus result in more severe anarithmetia (Grafmann, Passafiume, Faglioni, & Boller, 1982). What causes this?
- (2) Why is anarithmetia caused by left hemispheric lesions accompanied by marked spatial disturbances and linguistic problems (Dahmen, Hartje, Büssing, & Sturm, 1982)?
- (3) Among cases of anarithmetia caused by right hemispheric lesions, some patients with mild unilateral hemispatial neglect also display severe spatial anarithmetia. In a recent study, Grana, Hofer, and Smenza (2006) reported that anarithmetia is caused by visuospatial disturbances other than spatial attentional disturbances (e.g., unilateral hemispatial neglect) in cases involving right hemispheric injury. What is the causative mechanism of the anarithmetia in these cases? Why are there fewer reports of anarithmetia caused by right hemispheric injury than of anarithmetia caused by left hemispheric injury?

These questions could be answered by analyzing whether the spatial disturbances observed in patients with anarithmetia due to left or right hemispheric injury with no (or mild) aphasia, whose anarithmetia is unlikely to be caused by neglect, are caused by a mechanism that is common to both the right and left hemispheres, as well as the differences in the pathogenic mechanisms of right and left hemispheric lesions.

Here, we report a study of a 59-year-old, right-handed male patient with anarithmetia caused by cerebral infarction in the right-middle cerebral artery region, including a right posterior lesion, in order to address the above questions. Although this patient displayed left unilateral hemispatial neglect,

it did not influence his calculation ability, and he did not suffer from crossed aphasia.

The same patient developed a cerebral infarction in a region including the left inferior parietal lobule and the left angular gyrus 3 years later.

Here, we discuss how abnormal mental rotations caused by right and left hemispheric injuries affected the anarithmetia in this patient.

PATIENT AND METHODS

Case presentation

The patient was a 59-year-old right-handed Japanese male who suffered left hemiparesis a year prior to his admission to Hikone Municipal Hospital. Informed consent for this study was obtained from the patient and his wife. He was a junior high school graduate who had been working as a truck driver before suffering a cerebral infarction. On admission, a local doctor observed atrial fibrillation and infarction in the right-middle cerebral artery and right parietal and temporal lobes on computed tomography. The patient underwent rehabilitation and regained the ability to walk. His general condition was stable, and he was referred to Hikone Municipal Hospital to initiate warfarin treatment. This was his first admission to hospital. His neurological findings on admission included incomplete left hemiparesis, a hyperactive left deep tendon reflex, left hyperspasticity, and left hyperesthesia. His neuropsychological findings included left hemispatial neglect, left tactile extinction, constructional disorder, mild acalculia, mild finger agnosia, and mild agraphia. As acalculia was observed, which is rare in cases of right hemispheric damage, the patient was evaluated using the Mini-Mental State Examination (MMSE; Asada, Takaya, Takayama, Yamauchi, & Fukuyama, 2010; Folstein, Folstein, & McHugh, 1975); Hasegawa Dementia Scale Revised (HDS-R; Fukui et al., 2009); Raven Colored Progressive Matrices (RCPM; Raven, 1965); Wechsler Adult Intelligence Scale-Revised (WAIS-R, Japanese Edition; Asada et al., 2010; Wechsler, 1981); and Western Aphasia Battery (WAB; Kertesz, 1982), Japanese Edition (Sugishita, 1982). In addition, the patient's numerical ability was investigated, and his reading and writing abilities were also examined to rule out secondary acalculia (this included WAB testing). Damage to the right hemisphere and broad hypoperfusion of the middle cerebral

artery were observed on MRI and *N*-isopropyl-*p*-[123I]-iodoamphetamine single photon emission computed tomography (IMP-SPECT), while perfusion of the left hemisphere was maintained.

The patient subsequently made outpatient visits to hospital, and 3 years after the onset of symptoms he suffered a cerebral infarction in his left parietal lobe. As a result, he was subjected to a second round of evaluations, which also included neuropsychological examinations. It was difficult to perform even simple intelligence scale testing due to his impaired attention span and the fact that he became fatigued after a very short time. In the first evaluation, his WAB cortical quotient (CQ) scores were 83.05 (right hand) and 83.25 (left hand), whereas in the second evaluation his CQ scores were 42 (right hand) and 0 (left hand). His aphasia quotient (AQ) score was 90.3 in the first evaluation and had decreased to 78.3 by the second evaluation, when he showed mild aphasia. Regarding finger agnosia, he only made mistakes with his ring finger in both the first and second evaluations. In addition, in the second evaluations worse agraphia and the appearance of right-left disorientation were observed, and the patient was eventually unable to perform calculations.

Neuroimaging procedures

MRI was performed with a GE Signa Advantage 1.5 Tesla instrument during the first period of hospitalization and with a GE Signa LX, Ver 9.1, 1.5 Tesla instrument during the second period. IMP-SPECT was performed using a Gamma View-T instrument (Hitachi).

Neuropsychological assessment battery

Mini-Mental State Examination (MMSE)

The MMSE is a simple intelligence scale that mainly consists of verbal IQ items. These include arithmetic items, which account for 5 points out of 30.

Hasegawa Dementia Scale Revised (HDS-R)

The HDS-R is the most widely used simple intelligence scale in Japan and mainly consists of verbal IQ items. These include arithmetic items, which account for 5 points out of 30.

Raven's Colored Progressive Matrices (RCPM)

The RCPM is a battery of tests used to measure intellectual functions independently of language and is included in the WAB, which is described later.

Wechsler Adult Intelligence Scale (WAIS-R), Japanese edition

The WAIS-R is an intelligence test that assesses verbal and performance IQ separately. Arithmetic items are included among the verbal IQ items, but by assuming a perfect score for the arithmetic items it is possible to measure the effects of a reduced verbal IQ other than acalculia.

Low scores for the arithmetic tasks can be due to various disorders, such as an impaired understanding of arithmetic symbols, cognitive disorders, visuospatial cognitive disorders, and/or an impaired understanding of advanced arithmetic rules. Therefore, the causative mechanism of acalculia cannot be determined from the WAIS-R score alone (Lezak, 1995).

WAB Japanese edition

The WAB is a battery of tests for aphasia that has been standardized for Japanese subjects. It can be used to diagnose the type and severity of aphasia and to evaluate the condition in terms of the AQ. It can also be used to evaluate a subject's reading, writing, and construction abilities. The WAB includes the RCPM and so can be used to produce CQ and WAB scores. Arithmetic ability is measured by presenting written questions with multiple-choice answers. The subject replies to the questions by pointing to their preferred answer; therefore, the test is unaffected by writing ability. The WAB was used for arithmetic evaluations in this study because the arithmetic questions themselves can be separated out for evaluation and because no other tests contain questions that have been standardized for Japanese subjects.

WAB writing task

As mentioned earlier, the WAB can be used to evaluate both reading and writing. We investigated the subject's ability to copy and write down dictated sentences or numbers in order to investigate the relationship between arithmetic ability and reading. These tests were performed using in order of their appearance in the WAB: the sentence-copying tasks

were given first, followed by several other WAB tasks, and then written dictation. We were particularly interested in examining reading, writing, and the understanding of numbers.

WAB drawing task

Drawing is difficult for subjects with marked constructive disorders. We examined the subject's ability to produce a relatively simple vertical drawing of a tree. This tree-drawing task can be used to evaluate vertical spatial agnosia.

Number and calculation tasks

Understanding of numbers

Understanding of numbers: the subject's ability to understand large and small numbers and to pronounce, point at, copy, and write numerals were evaluated. Ability to count: the subject's ability to count 1 to 20 and backwards, and his ability to count the number of dots presented were evaluated. Knowledge of the four operations: the subject's ability to read the four arithmetic symbols and to use them in calculations were evaluated. Arranging in order of size: the subject's ability to arrange numbers composed of different numbers of digits in order of size was evaluated.

Performance of the four operations and procedures

Calculation tasks in the WAB: 24 WAB multiple-choice based calculation tasks (12 regular tasks and 12 supplementary tasks) were used for this evaluation. Two points were awarded for each correct answer, and no partial points were awarded; therefore, the maximum score for the 12 questions was 24 points. Mental calculation tasks: the subject's mental calculation ability was evaluated similarly using a total of 24 WAB arithmetic tasks (12 regular tasks and 12 supplementary tasks). Again, 2 points were awarded per question, and no partial points were awarded; therefore, the maximum score for the 12 questions was 24 points.

The difficulty level of all of the arithmetic questions was considered to be appropriate for an average 9-year-old elementary school student. For the regular tasks, the Japanese edition provides average score and standard deviation values for each age. A study of the WAB reported that the mean score

for 32 healthy subjects (31 subjects who were aged 25 or older and 1 who was <25 years of age) was 23.1/24 ($SD = 2.3$) (Sugishita, 1982).

Furthermore, it showed that the mean score for 191 aphasia patients (179 were aged between 25 and 75 years, 2 were aged <25 years, and 10 were aged >75 years) was 16.7/24 ($SD = 8.1$) (Sugishita, 1982).

The WAB Japanese edition does not provide any data for the supplementary tasks. In general, the regular tasks involved problems that would be encountered between the 1st to 3rd grades, while the supplementary tasks involved problems encountered in the 2nd and 3rd grades. The regular tasks involved simple addition and subtraction with no carrying of digits, the multiplication of single digits by single digits, and problems for which the correct answer was a single digit. The supplementary tasks involved addition and subtraction with the carrying of digits, and the addition and subtraction of 2 double digits, or 1 double digit and a 1 single digit. As well as the multiplication and division of single digits by single digits, they also included the multiplication of double digits by single digits and the division of double digits by double digits (Sugishita, 1982).

RESULTS

Neuroimaging studies (Figure 1)

First evaluation (1 year after the initial onset of symptoms)

At the time of the patient's first hospital admission, widespread infarction in the region surrounding the right-middle cerebral artery was observed on MRI T2-weighted images. Infarction was also observed in the parietal lobe, including the right angular and right supramarginal gyri, and the right temporal lobe. Broad hypoperfusion of the middle cerebral artery was observed on IMP-SPECT, while perfusion of the left hemisphere was maintained.

Second evaluation (3 years after the initial onset of symptoms)

New lesions in the left parietal lobe, including lesions in the left angular and left supramarginal gyri, were observed on fluid-attenuated inversion recovery (FLAIR) and T2-weighted sagittal MRI.

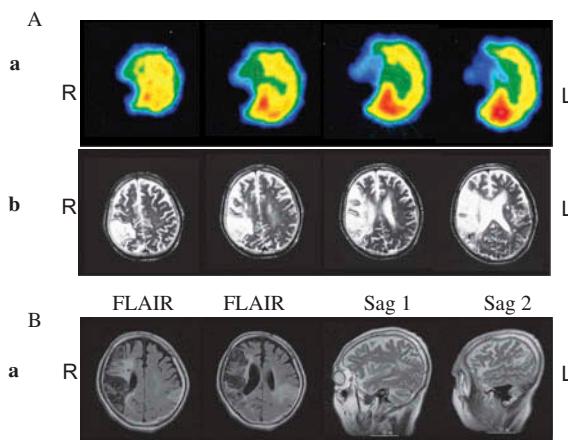


Figure 1. Findings from IMP-SPECT and MRI. (A) IMP-SPECT at the first admission showed decreased blood flow in the frontal, parietal, and temporal lobes of the right hemisphere (top image). Infarctions of the frontal, parietal, and temporal lobes of the right hemisphere were observed on the axial view (bottom image). (B) MRI performed at the second admission. The figure shows two axial FLAIR images and two sagittal T2-weighted images. In addition to the old cerebral infarction, new infarctions were observed in the parietal lobe of the left hemisphere, including the left angular gyrus and left supramarginal gyrus. [To view this figure in color, please visit the online version of this Journal.]

Neuropsychological assessment of intelligence (Table 1)

First evaluation

The patient's MMSE and HDS-R scores indicated a mild reduction of cognitive function, but the exclusion of items associated with arithmetic ability yielded scores within the normal range. His lower RCPM and performance intelligence quotient (PIQ) scores on the WAIS-R reflected the damage to his right hemisphere. As for his VIQ

TABLE 1
Neuropsychological assessment

Assessment Battery	First evaluation	Second evaluation
MMSE	24/30	ND
HDS-R	22/30	ND
RCPM	18/30	ND
<i>WAIS-R</i>		
VIQ	76	ND
PIQ	54	ND
FIQ	65	ND
<i>WAB</i>		
AQ	90.3	78.3
CQ (Right Hand)	83.05	42
CQ (Left Hand)	83.25	0

(verbal intelligence quotient) score on the WAIS-R, his subtest score for arithmetic items was noticeably lower than that for the other tests. If he had achieved a perfect score for the arithmetic items, his VIQ score would have been >80 , which is within the normal range.

Second evaluation

The tests could not be performed because the subject had difficulty concentrating.

WAB (Table 2)

First evaluation

The patient's AQ score was 90.3, indicating that he did not have aphasia. His CQ score, which is an evaluation of cognitive function based on the entire WAB, was 83.05 for the right hand and 83.25 for the left hand, indicating that there was no clear reduction in his cognitive function. A moderate reduction was observed in his constructive ability, reflecting the damage to his right hemisphere. Hemispatial neglect was also observed in the line bisection test.

Second evaluation

His AQ score was 78.3, indicating mild aphasia. His CQ score was 42 for the left hand and 0 for the right hand, indicating a clear reduction in his cognitive function. In the line bisection test, we found that his hemispatial neglect had disappeared.

WAB reading and writing

First evaluation

Almost no reading disturbance was observed. Mild writing disturbance was detected. The patient copied a vertical writing sample in a horizontal orientation and wrote dictated words horizontally. When writing numbers of his own accord (or answering dictated questions), he wrote in a vertical orientation.

Second evaluation

A marked reduction in his overall reading ability was observed. His reading ability at the word level was relatively well conserved, but his understanding of sentences was reduced. A marked general

TABLE 2
Western Aphasia Battery (WAB) assessment in 1st and 2nd evaluation

	Score		
	1st	2nd	
Spontaneous speech	18	17	
Understanding of speech	8.15	7.35	
Repetition	10	7.7	
Naming	9	7.1	
Reading	8.5	3.45	
Writing	7.4	2.15	
Behaviour (right hand)	9.5	7	
Behaviour (left hand)	9.7	0	
Construction	5.35	0.7	
Aphasia Quotient (AQ)	90.3	78.3	
Cortical Quotient (CQ-right hand)	83.05	42	
Cortical Quotient (CQ-left hand)	83.25	0	

reduction in writing ability was observed, but his ability to write numbers of his own accord or in response to dictation were relatively well conserved.

The patient copied vertical writing in the same orientation, and wrote dictated words vertically. Numbers that he wrote of his own accord were written horizontally, as were his responses to dictation.

WAB finger agnosia and right-left disorientation

First evaluation

He only made mistakes with his ring finger. No right-left disorientation was observed.

Second evaluation

He still only made mistakes with his ring finger. However, he made mistakes regarding both the right and left body regions.

WAB drawing evaluation

First evaluation

With the exception of a tendency to slant writing in a horizontal direction (toward the x -axis in an xy -axis system), the patient had the ability to draw of his own accord. However, when drawing a picture of a tree, he drew the trunk and branches, but only to a degree that permitted distinction between the top and bottom of the tree, and his drawing was clumsy. The subtest items indicated moderate constructional disturbance because the figure drawn by the patient was relatively accurate.

Second evaluation

The test could not be performed because the subject had difficulty maintaining his concentration.

Number and calculation tasks

Understanding of numbers

In the first evaluation, the patient was able to understand large and small numbers, and to pronounce, point at, copy, and write numbers. In the second evaluation, he was able to point at all numbers spoken during the WAB tasks. He was also able to point at the correct option in all tasks involving choosing numbers of up to 4 digits in length. These

results showed that his auditory comprehension of numbers was relatively well preserved. However, when the number 712 was presented to him, he pronounced it as “seven, one, two.”

Ability to count

In the first evaluation, the patient was able to count from 1 to 20 as well as in reverse. He could also count 7 dots that were presented to him. During his second hospital admission, when he was counting from 1 to 20, he counted from 1 to 6 and then stopped due to concentration difficulties. Then, after a short pause, he said 7 and 8 and then counted up to 11 and 12, after which he found it very difficult to continue. He also found counting backwards from 20 difficult. He was able to count dots, but had trouble understanding a task involving adding up numbers of dots.

Knowledge of the four arithmetic operations

In the first evaluation, the patient was able to read and write the four arithmetic symbols and use them in calculations. In the second evaluation, he was asked to perform written calculation tasks. Because he read $5 + 4 =$ as 54, the examiner pointed at the “+” symbol. Then, the patient responded with the word “plus.” When the examiner presented the subject with the oral calculation task $6 - 2$, he answered 4, and he clearly understood subtraction. However, when the same sum was presented as a written calculation task he answered it 62. He was unable to perform multiplication tasks presented to him by the examiner. However, when the patient was asked what was 4×2 and was allowed to use a multiplication table, he answered 8. He almost completely understood addition and subtraction.

Arranging numbers in order of size

In the first evaluation, the patient was able to arrange numbers containing different numbers of digits in order of size. In the second evaluation, he was unable to arrange numbers in order of size.

Performance of the four arithmetic operations and procedures (Table 3)

WAB

In the arithmetic tasks, the subject scored 24/24 on the regular tasks (related to overall WAB

TABLE 3
Calculation assessments

Assessment Battery	First evaluation	Second evaluation
<i>WAB Task: Multiple-choice method</i>		
Regular Task	24/24	0/24
Supplementary Task	12/24	0/24
Total	36/48	0/48
<i>WAB Task: Mental calculation</i>		
Regular Task	20/24	0/24
Supplementary Task	6/24	0/24
Total	26/48	0/48

CQ) and 12/24 on the supplementary tasks (not related to overall WAB CQ). Most of the correct answers he gave in the supplementary tasks were for simple tasks, such as $7 + 5$, $11 - 4$, etc.

As unilateral hemispatial neglect was observed, we examined the possibility that the incorrect answers were due to the patient overlooking digits on his left side; however, none of the errors could be attributed this.

In the second evaluation, the patient was unable to perform calculations. He also read $5 + 4$ = as 54, $6 - 2$ = as 62, and $9 - 7$ = as 97. Regardless of whether the task was in multiple-choice format or involved mental calculation, he said that he did not know the answer. When the examiner pointed at the addition symbol, the patient responded with "plus." However, he hesitated between 9 and 20 regarding the answer to $5 + 4$ = in the multiple-choice task. Similarly, he was unable to choose an answer for the 4×2 = multiple-choice based written calculation task, but he correctly answered the same question when using multiplication tables. Although he also correctly answered the sum 8×8 = using the multiplication table, he was unable to answer $64 \div 8$ = in the multiple-choice task. When horizontally written calculation tasks; i.e., 5×3 = and 6×7 =, were presented, he was unable to perform the calculations, which was also the case for written addition and subtraction questions.

Mental calculation tasks

In the first evaluation, 24 tasks (12 regular tasks and 12 supplementary tasks) were used to evaluate the subject's mental calculation ability. The scoring method was the same as that used for the multiple-choice questions discussed above. The patient's score for the regular tasks was 20/24 and that for the supplementary tasks was 6/24, and he made mistakes whilst adding 2-digit numbers.

In the second evaluation, the patient had difficulty performing the WAB tasks, as mentioned above. However, he successfully performed follow-up tests including the WAB tasks and correctly answered the mental calculation " $5 + 4 = 9$."

DISCUSSION

As two different lesions were examined in a single patient in this study, we should have assessed the activation of homologous contralateral areas and the cortices surrounding the lesions in the right and left hemispheres with functional MRI or ^{18}F -fluorodeoxyglucose positron emission tomography (FDG-PET) in order to evaluate neural activity; however, these assessments could not be performed due to institutional limitations. At the time of the left hemispheric injury, 3 years had elapsed since the onset of the right hemispheric injury, and the patient's left unilateral hemispatial neglect had disappeared. Thus, the functions of his right parietal lobe might have recovered from interhemispheric suppression by the left hemisphere, at least to some extent, by the time of the left hemispheric injury.

Moreover, we were unable to confirm the influence of suppression from the cortex around the left hemispheric lesion at the time of the left hemispheric injury. Regarding the injury to the left parietal lobe, our patient did not present with motor aphasia, but abnormal mental rotation was observed. Thus, based on a simple double dissociation (Teuber, 1955), we concluded that the second infarction; i.e., the parietal lesion in the left hemisphere (including the left angular gyrus and the left supramarginal gyrus) had caused abnormal mental rotation toward the vertical direction.

Anarithmetia caused by right hemispheric injury in this patient

At the time of the right hemispheric injury, the patient wrote down spoken numbers in ascending order from 1 to 20 vertically. This suggests that writing numbers in the vertical direction helped the patient to understand them; i.e., the independence of the numbers was clearer to the patient when he wrote them in the vertical direction than when he wrote them in the horizontal direction. However, he consistently wrote letters in a horizontal direction. Thus, letters might have been clearer to the patient when they were written in the horizontal direction. This hypothesis does not contradict his vertical

writing of numbers if each number is considered as an independent entity. One of the characteristics of the patient's anarithmetia at the time of the right hemispheric injury was that he was able to perform subtraction involving 2-digit numbers that did not require a carrying or borrowing operation, while he found calculations involving even 2-digit numbers that required a carrying or borrowing operation difficult. In order to facilitate calculation, the formula involved should ideally be written in the vertical direction. Given the patient's inclination towards the horizontal direction in the mental rotation of words and numbers, this vertical pattern might have been consciously converted to a horizontal pattern, which would have affected carrying and borrowing operations. The patient did not have aphasia in terms of reading numbers, words, etc.

Anarithmetia caused by left hemispheric injury in this patient

In the first examination, the patient exhibited a mental image manipulation disturbance that caused him to copy vertical text in a horizontal format, which is characteristic of right hemispheric damage. Due to the subsequent left hemispheric damage, he read 712 as a row of numerals "seven, one, two," and read the written calculation $5 + 4$ vertically as "54." Reading 712 as "seven, one, two" is also observed in Wernicke's aphasia (Deloche & Seron, 1987). However, the patient's performance on yes/no type questions was better than that observed in typical Wernicke's aphasia. Furthermore, his AQ score was indicative of relatively mild aphasia. Therefore, the abovementioned mistake was unlikely to be associated with Wernicke's aphasia. With regard to reading the written calculation $5 + 4$ vertically as "54," a similar phenomenon occurs in cases of hemispatial neglect because the "+" sign is ignored. However, hemispatial neglect was not observed in the second evaluation, as shown by the line bisection test (Figure 2B). Therefore, these incorrect responses were thought to have arisen from a mental image creation disturbance, which is characteristic of left hemispheric damage. As a vertical directional inclination due to left hemispheric damage was also present, the patient's mental image disturbance might have been caused by the same mechanism; i.e., damage to the left hemisphere.

Based on the above findings, the patient tended to write numbers spoken in ascending order

horizontally, in contrast to anarithmetia caused by right hemispheric injury. He might have been inclined towards the vertical direction when writing words after left hemispheric injury.

In contrast, at the time of the right hemispheric injury, horizontally arranged numbers were

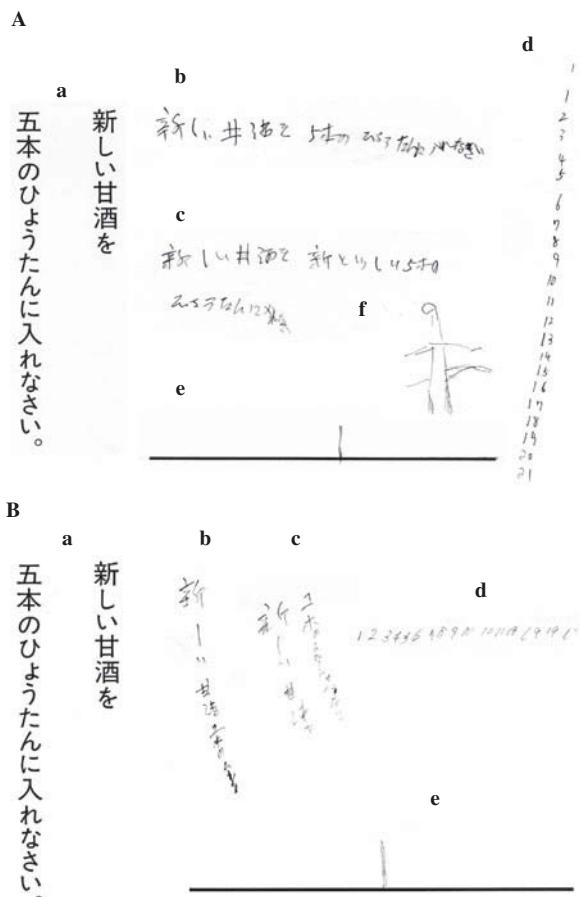


Figure 2. (a) Sample used for writing and reading in the WAB; (b) copying model (a); (c) writing after dictation; (d) writing numbers 1 to 20 (spontaneous writing without reference to the model); (e) the line bisection test; and (f) drawing a tree (only the tree drawn in the first evaluation is shown: the patient was unable to draw anything in the second evaluation). (A) First evaluation. Relative to (a), (b) was written horizontally, as was the writing in (c). However, the numbers in (d) were written vertically. Unilateral hemispatial neglect was observed in the line bisection test in (e). In (f), the patient drew a seemingly dead tree (probably because it was winter), but the positional relationship between the trunk and branches was correctly portrayed. The drawing was almost symmetrical, which made it difficult to judge whether it was a mirror image. (B) Second evaluation. Relative to (a), (b) was vertical, as was the writing in (c). However, the right and left characters in the lines were reversed (in Japanese script, writing vertically from the left, as shown in the model, is normal). In (d), the numbers were written horizontally, but "19" was written correctly. There were no abnormalities in the line bisection test (e).

perceived in the vertical direction. For example, he would have the horizontally arranged number 123 as three independent numbers (1, 2, and 3). Moreover, this inclination was assumed to have affected the patient's ability to read numbers because he read 712 as "7, 1, and 2" and read the horizontally written calculation tasks in the vertical direction.

A hypothesis regarding the mechanism of the anarithmetia in our patient

In light of these findings, we suggest that one possible reason why no Western studies have observed agraphia caused by damage to the right hemisphere is that horizontal writing is normal in the West, which could render the detection of anomalies difficult. In contrast, Asian languages, including Japanese are written vertically as often as they are horizontally, particularly when writing letters, which facilitates the detection of writing anomalies in the horizontal direction caused by damage to the right hemisphere.

Arabic number reading or writing might not be affected by agraphia or alexia (Anderson, Damasio, & Damasio, 1990; Starrfelt, 2007), as has already been described in a case of pure alexia (Dejerine, 1892; Furukawa, 2009). In our case, the assessments of number reading and writing did not produce identical results to the tests examining the writing and reading of letters or sentences. In the second evaluation, differences between the writing and reading of numbers were observed. These results might not have been caused by alexia or agraphia, but rather from the meaning of the numbers in the patient's mind. For example, during number writing in the second evaluation the patient wrote the numbers horizontally, which might have been a category separation technique, as he read "712" as "seven, one, two" (Basso et al., 2000).

Although there were differences in the direction-vector abnormalities between the left and right hemispheres, the present patient displayed a mental image manipulation disturbance in the right hemisphere after their initial injury, and a mental image creation disturbance following the subsequent damage to the left hemisphere, resulting in differences in the ease of orientation in the horizontal and vertical directions. The conventional hypothesis is that mental image manipulation disturbances occur after damage to the right hemisphere and mental image creation disturbances occur following damage to

the left hemisphere (Gill, O'Boyle, & Hathaway, 1998; Newcombe & Ratcliff, 1989).

In our patient, the anarithmetia that occurred after the injury to his left posterior parietal lobe might have been caused by mental rotation abnormalities in the vertical direction.

In a previous study on the brain localization of mental images in healthy subjects, Thompson and Kosslyn (2000) performed a meta-analysis of neuroimaging data and observed activation of the posterior parietal lobe during tasks requiring imaging processes such as mental rotation. This suggested that the posterior parietal lobe plays an important role in mental imaging. Sereno, Pitzalis, and Martinez (2001) reported that spatial representations are composed of local representations in multiple areas of the posterior parietal lobe.

In a previous study of brain injury patients, Levine, Warach, and Farah (1985) described visual disorientation in patients with parietal injuries. In addition, Farah, Levine, and Calvano (1998) described a single case of left posterior cerebral infarction involving a mental image disorder and speculated that their patient's disturbance might have originated from discrepancies between mental images and language.

Subsequently, Stanglino investigated 70 unilateral brain damaged patients in a study of mental image generation disturbance and found that image generation disturbance was more frequent in patients with left posterior cerebral damage (Stanglino, Semenza, & Mondini, 1995).

All the above studies support our suggestion that in the present case severe anarithmetia occurred due to imaging disturbances such as mental rotation abnormalities caused by the lesion in the left posterior parietal lobe.

Regarding the relationship between mental rotation and acalculia, mental rotation disturbance due to a subangular lesion is known to be the basis of Gerstmann's syndrome, which includes acalculia (Mayer et al., 1999; O'Boyle et al., 2005; Rusconi, Pinel, Dehaene, & Kleinschmidt, 2010). Although disorders pertaining to mental rotation abilities are frequently the result of parietal lobe lesions, particularly in the right hemisphere (Corballis, 1997; O'Boyle et al., 2005), our case suggests that the deviation of mental rotation toward a different direction can occur in both hemispheres. Moreover, our results indicate that acalculia might also occur as a result of damage to the right hemisphere through the same mechanism, but with a different directional (horizontal) anomaly to that caused

by left hemispheric injury (vertical). Factors independent of language might also have caused the inter-hemispheric differences in acalculia observed in the present case.

CONCLUSION

Based on the above findings, the anarithmetia in our patient was considered to be attributable to the inclination of mental rotation toward the horizontal direction at the time of the right hemispheric injury and toward the vertical direction at the time of the left hemispheric injury. The lesions included the parietal lobe posterior to the central gyri in both hemispheres. In the left hemisphere, the left parietal lobe lesion included the left angular gyrus and the left supramarginal gyrus.

Our findings suggest the following answers to the questions posed in the introduction section:

1. **It has been shown that lesions located posterior to either central gyrus result in more severe anarithmetia (Grafmann et al., 1982). What causes this?**

Mental rotation might be mainly affected by lesions posterior to the central gyrus, and so lesions in this region result in severe anarithmetia.

2. **Why is anarithmetia caused by left hemispheric lesions accompanied by marked spatial disturbances and linguistic problems (Dahmen et al., 1982)?**

Due to mental rotation toward the vertical direction, severe anarithmetia was observed following left hemispheric injury.

3. **What is the causative mechanism of anarithmetia caused by right hemispheric injury? Why are there fewer reports of anarithmetia caused by right hemispheric injury than of anarithmetia caused by left hemispheric injury?**

The inclination of writing and mental rotation toward the horizontal direction observed in our patient after the right hemispheric injury might have been associated with his anarithmetia. Based on this, the tendency to manipulate written calculation tasks in the horizontal direction might have been a factor in the anarithmetia displayed by the patient during written calculations. In addition, the patient's incorrect reading of numbers due to his inclination to view them in the vertical direction following his left hemispheric injury might also have contributed

to his anarithmetia. Moreover, while writing in the vertical direction is common in Japan, China, and Korea, writing in the horizontal direction is normal in most cases in Western countries. This might have contributed to the fact that anarithmetia caused by right hemispheric injury is considered to be mild and rare. Further studies might be needed to determine whether this causes differences among ethnic groups.

It should be noted that this report only involves a single case. To confirm our hypothesis, we should clarify the relationship among mental rotation disturbance, anarithmetia, and posterior lesions, and investigate the differences between right and left posterior lesions in terms of reading and writing ability, in horizontal and vertical directions.

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