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The role of movement representation in episodic memory for actions: A study of patients with apraxia

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In attempting to memorize a sentence about an action, such as "Pick up the glass," performing the action (motor encoding) results in better memory performance than simply memorizing the words (verbal encoding). Such enhancement of memory is known as the enactment effect. Several theories have been proposed to explain this phenomenon using concepts such as physical motor information associated with speed, form, amplitude of movement and/or movement representations involved in movement imaging, knowledge on manipulating tools, and spatial relationships in the enactment effect. However, there have been no cognitive neuropsychological studies investigating whether the enactment effect is crucially influenced by physical motor information or movement representations. To clarify this issue, we compared healthy adult control participants with two different types of apraxia patients. One patient with left hemisphere lesions caused by cerebral infarction had a disability involving multiple movement representations. The other patient showed symptoms of corticobasal syndrome and was not able to benefit from feedback on the accuracy of her motor movements during enactment. Participants memorized action sentences via either verbal or motor encoding and responded to recall and recognition tests. Results indicated that the patient with the movement representation deficits exhibited worse memory performance than the other patient or control participants following both verbal and motor encoding. Although the enactment effect was present during recall in both patients, the effect was not observed for recognition in the patient with severe movement representation deficits. These results suggest that movement representations are involved in encoding episodic memories of action. Moreover, the role of movement representations appears to depend on the form of retrieval that is being used.

Keywords: Enactment effect; Subject-performed task; Apraxia; Memory of actions; Movement representation.

Since the 1980s, many studies have reported that motor encoding enhances episodic memory performance (Cohen, [1989](#page-11-0); Nilsson, [2000](#page-12-0)). For example, when memorizing an action sentence such as "pick up a glass," enacting the movements prescribed by the sentence (motor encoding) results in better memory performance than simply memorizing the sentence (verbal encoding). This memory enhancement has been termed the SPT (subject-performed task; e.g., Cohen, [1989](#page-11-0)) effect or enactment effect (e.g., Nyberg, Persson, & Nilsson, [2002\)](#page-12-0). To date, the enactment effect has been investigated in elderly adults who show declines in episodic memory performance (Bäckman & Nilsson, [1984](#page-11-0), [1985](#page-11-0); Nyberg et al., [2002](#page-12-0)), Alzheimer's disease patients (Hutton, Sheppard, Rusted, & Ratner, [1996](#page-11-0); Karlsson et al., [1989](#page-12-0); Masumoto, Takai, Tsuneto, & Kashiwagi, [2004](#page-12-0)), and Korsakoff patients with severe anterograde amnesia (Mimura et al., [1998\)](#page-12-0). For example, Karlsson et al. ([1989](#page-12-0)) conducted free recall and cued recall tests under motor and verbal encoding conditions for two groups of normal older adults (73 and

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82 years old) and three groups of Alzheimer's disease patients (with mild, moderate, and severe dementia). They reported that all groups performed better on motor encoding than on verbal encoding, and for all groups, cuing effects were greater for motor than for verbal encoding. In short, comprehensive research on the enactment effect indicates that it is very robust.

Several theories outline the cognitive processes that are thought to mediate memory enhancement through motor encoding (Nilsson, [2000\)](#page-12-0). For example, Bäckman and Nilsson ([1985\)](#page-11-0) proposed a multimodal encoding model that attributes the enactment effect to multimodal and enriched properties. During motor encoding, this model states that participants obtain visual and tactile information about a tool or body part along with both physical movement information and verbal information by performing the action indicated in a sentence. Motor encoding leads to better memory performance than verbal encoding by providing this breadth of information. Other theories, including the one proposed by Engelkamp [\(1998](#page-11-0)), suggest an association with the item-specific processing framework. This theory assumes three encoding processes: sensory, semantic, and motor. It emphasizes the fact that motor encoding is more efficient than other forms of sensory (e.g., visual, auditory, olfactory) or semantic encoding, and that motor encoding improves item-specific processing. Similar to the multimodal encoding model, this theory assumes that physical motor information, including kinematic components such as speed, form, and amplitude, works to create the enactment effect. In contrast, the episodic integration theory proposed by Kormi-Nouri [\(1995\)](#page-12-0) proposes that the process of encoding physical motor information is not important for memory enhancement, but rather that the self-involvement produced by enactment facilitates semantic and episodic integration between the noun and verb in an action sentence. In other words, the enactment integrates encoding of an action verb and a noun into a single memory unit (Nilsson, [2000](#page-12-0)).

As outlined above, several competing theories have been proposed regarding memory enhancement through motor encoding. An important issue concerning the enactment effect is whether physical motor information resulting from enactment plays a crucial role in memory enhancement. Several studies using brain imaging methods such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), and magnetoencephalography (MEG) have examined this issue. These studies have been conducted based on reactivation theory, in which regions of the brain that are activated during the encoding of specific sensory information are thought to be reactivated during retrieval

(Sakai, [2003;](#page-12-0) Wheeler, Petersen, & Buckner, [2000](#page-12-0)). According to the reactivation theory, if the enactment effect is due to retrieval of physical motor information through motor encoding, brain regions related to motor function should be reactivated during retrieval of the verbal action sentences. In PET studies, it has been reported that motor cortex activity increases during cued recall following motor encoding (Nilsson et al., [2000](#page-12-0)), and direct comparisons of brain activity during encoding and retrieval provide evidence of contralateral motor cortex reactivation (Nyberg et al., [2001](#page-12-0)). In MEG studies, reactivation of the primary motor cortex suggests that physical motor information derived from enacted encoding is involved in the enactment effect (Masumoto et al., [2006](#page-12-0)).

An fMRI study reported that activity in the bilateral parietal cortices, especially in the inferior parietal cortex/supramarginal gyrus (SMG), shows a robust increase during recognition performance following enacted encoding compared with verbal encoding (Russ, Mack, Grama, Lanfermann, & Knopf, [2003](#page-12-0)). Similarly, studies using MEG (Masumoto et al., [2006](#page-12-0)) and PET (Nyberg et al., [2001](#page-12-0)), in which reactivation of the motor region was found, have also reported increased parietal cortex activity during retrieval following motor encoding. Russ et al. ([2003](#page-12-0)) suggested that the parietal cortex, particularly the SMG, plays an important role in the enactment effect and that enactment effect related processing is based on more complex higher order cognitive systems than those operating at the level of the primary motor cortex.

Although these functional brain imaging studies can provide evidence of neurobiological measures that are related to the cognitive processes associated with the enactment effect, these studies do not constitute a sufficient basis for determining the importance of cognitive processes in the enactment effect. The purpose of the present cognitive neuropsychological study was to elucidate whether motor information or movement representations play an important role in the enactment effect. Lesions of the parietal cortex, particularly in the left hemisphere, frequently lead to apraxia, which involves deficits in the production of actions that involve giving commands, pantomime, imitation of gestures, and/or use of tools. Research on the parietal cortex in apraxia has been conducted from different viewpoints and different theoretical approaches (Goldenberg, [2009\)](#page-11-0), with previous neuropsychological studies focusing on the role of the left parietal cortex in apraxia. For example, the parietal cortex is associated with mental images of movement (Buxbaum, Johnson-Frey, & Bartlett-Williams, [2005;](#page-11-0) Sirigu et al., [1996](#page-12-0)), sensorimotor

knowledge about tool manipulation (Buxbaum, [2001](#page-11-0)), and knowledge of skilled purposeful movements (Buxbaum, Sirigu, Schwartz, & Klatzky, [2003](#page-11-0)). Recently, Goldenberg ([2009](#page-11-0)) reported parietal lobe involvement in interference effects between imitation and tool use associated with apprehension of spatial relationships between the body part and tool. Osiurak ([2014](#page-12-0)) proposed a theoretical framework for explaining tool use, proposing that technical reasoning consists of mechanical knowledge and objectbased knowledge, along with a production system involved in planning and controlling body movements. These elements are supported by the left inferior parietal (ventrodorsal stream) and superior parietal lobes (dorsodorsal stream), respectively.

In this study, we compared healthy adult control subjects to two different types of apraxic patient. One patient had left hemisphere lesions that involved the parietal lobe and showed severe orofacial and limb apraxia with deficits in producing meaningful gestures on command, imitating meaningful gestures, pantomime, and tool use. This patient produced inaccurate hand postures and tool grasping motions, showed substitution of purposive movement with different movements, and misused tools. It would appear that her parietal lesions had an impact on multiple forms of movement representations (spatial representations, movement motor imagery, and knowledge of body part and tool manipulation). Thus, this patient was not expected to benefit from enactment-related semantic and episodic integration between the noun and verb in an action sentence, due to an impaired ability to form complex movement representations. The other patient showed blood flow reductions to the parietal lobe and basal ganglia caused by brain shrinkage. Her movements were clumsy and awkward but she was able to enact purposeful actions. However, the patient was not able to receive accurate feedback regarding her purposive movements. We hypothesized that if movement representations are an important factor in the enactment effect, the former patient would not show the enactment effect, which should be observed in the latter patient. Conversely, if physical motor information is important, the enactment effect should enhance memory performance for only the former patient.

Generally, it is difficult to conduct verbal memory tasks with apraxia patients, given that apraxia is often accompanied by aphasia. Therefore, there are no prior reports of the enactment effect in apraxia in patients. Though apraxia is frequently found in patients with Alzheimer's disease, such studies have focused on the relationship between severe memory disorder and the enactment effect,

with no examinations of potential relationships with apraxia.

METHOD

Patient K.T.

Patient K.T. was a right-handed Japanese speaker. She was a housewife with a high-school education (12 years). At the time of the experiments, she was 68 years old and had suffered a left middle cerebral artery stroke three months earlier. She underwent conservative management.

Apraxia evaluation

Facial movement. We evaluated intransitive and transitive orofacial movements [\(Table 1\)](#page-4-0). On the intransitive, we used nine orofacial movements (click tongue, puff out cheeks, whistle, wink, lick lips, open mouth, cough, hold breath, and harrumph). We asked K.T. to obey oral commands and to imitate the examiner. Her performance was 4/9 correct in executing oral commands and 7/9 correct for imitation. Her errors were mainly of the content variety (e.g., instead of clicking her tongue she clicked her teeth). For the transitive orofacial movements, we tested pantomime (by oral commands and imitation) and tool use via oral commands. The nine movements were "smell flower," "suck through a straw," "suck on a candy," "blow out the match," "bite into an apple," "blow a windmill," "chew gum," "use toothpick," and "blow up a balloon." She correctly performed 6/9 pantomimes by oral command, 8/9 pantomimes by imitation, and 8/9 examples of tool use by oral commands. K.T. again showed content errors, particularly during pantomime (e.g., "suck on a candy" was replaced by "lick upper lip").

Limb movement. We assessed 10 intransitive movements via oral commands and imitation: "beckon with the hand," "snap fingers," "wave goodbye," "make a salute," "scratch head," "make a fist," "make an OK sign," "show scissors," "pinch nose," and "wave hand in front of face." For the intransitive trials, K.T.'s correct responses were 6/10 oral commands and 9/10 imitations. Additionally, we assessed nine transitive movements via pantomime (oral commands and imitation) and tool use (oral commands and imitation). The nine movements were "use scissors," "pound a nail with a

	Type	Output	Modality	Patient		
Movement				K . T .	O.T.	
Orofacial movement	intransitive	gesture	oral command	4/9		9/9
				7/9	9/9	
	transitive	pantomime	oral command	6/9	7/9	
			imitation 8/9		9/9	
		use of tools	oral command	8/9	8/9	
					Left hand	Right hand
Limb movement	intransitive	gesture	oral command	6/10	5/10	2/10
			imitation	9/10	5/10	3/10
	transitive	pantomime	oral command	3/9	1/9	0/9
			imitation	9/9	2/9	0/9
		use of tools	oral command	3/9	4/9	0/9
			imitation	7/9	4/9	0/9
Serial movement			0/2	1/2		
Verbal explanation of how to use tools			possible	possible		

TABLE 1 Correct response of movement evaluation in K.T. and O.T.

hammer," "brush teeth," "comb," "turn a nut with screwdriver," "write in pencil," "saw timber," "open lock with key," and "use a fork." For the transitive movements, pantomime performance was 3/9 for the oral commands and 9/9 for imitation, and tool use performance was 3/9 correct for oral commands and 7/9 for imitation. Oral commands yielded more errors than imitation, regardless of the transitive or intransitive nature of the movements. Content errors predominated; for example, she snapped her fingers instead of making an OK sign. She also showed a delayed response to opening a lock with a key and error of body part as object at brushing teeth.

On serial movements such as "take a match out of a box, strike it, and light a candle," K.T. tried to light a candle without striking the match, although she could verbally explain how to use tools. We confirmed that her right–left orientation was preserved, based on commands such as "touch your right ear with your left hand" and "touch my right ear with your left hand."

Above assessments revealed that there were deficits across multiple movement representations (spatial representation of movement, movement imagery, and/or knowledge of manipulation). Some imitation and tool use errors suggested impaired spatial representation of movements. The apraxia in K.T. was primarily classified as ideational and ideomotor apraxia. The classification was derived from dysfunction of the patient's conceptual system-associated integration between the functional knowledge of actions and those involved in object knowledge. The latter was caused by dysfunction of the production system and the perceptual motor processes for organizing or executing actions (Leiguarda & Marsden, [2000](#page-12-0)).

Despite her normal language abilities (intact auditory comprehension and verbal understanding of the purpose of movements and tool usage; see below), she evidenced substitution and misuse errors. Semantic (functional) and manipulation knowledge appear to be stored separately, with several studies suggesting a relationship between the parietal cortex and manipulation knowledge (for reviews, see Goldenberg, [2009;](#page-11-0) Goldenberg & Spatt, [2009;](#page-11-0) Osiurak, [2014](#page-12-0)). This patient appeared to have a severe manipulation knowledge deficit.

Cognitive functioning

Cognitive tests ([Table 2](#page-5-0)), including the Rey Auditory Verbal Learning Test (RAVLT; repeated learning $= 5-5-7-8-9$, delayed learning $= 5/15$), story recall test (immediate recall $= 7/15$, 5-min delayed recall = $6/15$, 60-min delayed recall = $6/$ 15), and digit span test (forward $= 6$, backward $=$ 7), revealed normal performance on repeated learning, immediate recall, delayed recall, and memory span. According to a normal score on the Raven's Colored Progressive Matrices (RCPM) test, K.T.'s intelligence also remained intact.

Language ability was evaluated using the Token Test and Standard Language Test of Aphasia (SLTA; Hasegawa, Kishi, Shigeno, Tanemura, & Kusunoki, [1985](#page-11-0)). The SLTA is the standardized test battery most commonly used to assess aphasia in Japan. These tests revealed that K.T.'s language abilities were generally maintained; Token Test = 160/165; SLTA, repetition (word $= 10/10$, sentence $= 10/10$, pronunciation (words written in kanji $=$ 10/10, kana = 10/10, and short sentences = $10/10$),

 $Note$ MMSE = Mini-Mental State Examination; RAVLT = Rey Auditory Verbal Learning Test; RCPM = Raven's Colored Progressive Matrices.

naming objects presented by pictures = 19/20, reading comprehension (kana letters 10/10, kanji letters 10/10, short sentences 8/10, obeying written commands $8/10$), auditory comprehension (words = $10/$ 10 short sentences $= 8/10$, obeying auditory commands = $8/10$). However, K.T. did show severe agraphia (SLTA; dictation of kanji = $0/10$, kana = $0/10$, short sentences = $0/10$). Dysarthria was not observed, and spontaneous speech was fluent.

K.T.'s visuospatial task performance (copy of Rey–Osterrieth Complex Figure Test, cube copy, block construction task, and line bisection task) showed no evidence of visual cognitive dysfunction such as unilateral neglect and suggested normal visuospatial construction ability.

Imaging

A magnetic resonance imaging (MRI) scan taken after her stroke showed abnormal signal intensity in the left parietal cortex (Figure 1). T2-weighted imaging revealed an extensive cerebral infarction in the territory of the left middle cerebral artery impinging on the superior and middle temporal lobe, the posterior part of the inferior temporal lobe, and the whole inferior parietal lobule, spreading extensively to the deep white matter including the pyramidal tracts and structures such as the lenticular and caudate nuclei. She also experienced paralysis on the right side of the body.

Patient O.T.

Patient O.T. was a right-handed Japanese speaker. She was a housewife with a junior high-school education (nine years). At the time of the experiments, she was 72 years old.

Apraxia evaluation Apraxia evaluation

We conducted the same evaluation as that administered to K.T. ([Table 1\)](#page-4-0).

Facial movement. On the intransitive trials, there were no oral command or imitation errors. On the transitive orofacial movements, O.T. got 7/ 9 correct for pantomiming oral commands, 9/9 correct for pantomiming by imitation, and 9/9 correct for tool use via oral commands. The pantomime oral command error involved the production of extra movement, such that the patient breathed before sucking on a candy.

Limb movemen. We carried out an assessment of the patient's left and right hands. For intransitive movements with the left hand, correct responses were 5/10 for oral commands and 5/10 for imitation. With the right hand, correct

Figure 1. T2 density weighted image from a magnetic resonance imaging (MRI) scan for K.T. To view a color version of this figure, please see the online issue of the Journal.

responses were 2/10 for oral commands and 3/10 for imitation. For transitive movements with the left hand, pantomime performance was 1/9 for oral commands and 2/9 for imitation, and tool use performance was 4/9 for oral commands and 4/9 for imitation. With the right hand, pantomime performance was 0/9 for oral commands and 0/9 for imitation, and tool use performance was 0/9 for oral commands and 0/9 for imitation.

O.T.'s movements were clumsy and awkward for oral commands, imitation, pantomime, and tool use. The apraxia in O.T. was classified as limbkinetic apraxia caused by corticobasal syndrome. Limb-kinetic apraxia consists of impaired, coarse, mutilated execution of simple movements, with more complex motions likely not possible (Denes, Mantovan, Gallana, & Cappelletti, [1998](#page-11-0); Leiguarda, Merello, & Balej, [2000](#page-12-0)). Additionally, she showed two substitution errors for intransitive movements and one substitution error for transitive movements. Thus, her apraxia was also classified as ideomotor apraxia and ideational apraxia, though they were very mild compared to those of K.T. She gave up attempts to perform several movements with her right hand, because she could not move her hand smoothly and could not grasp tools due to rigidity. She could verbally explain tool use.

In addition to these movements, we assessed "reach into your pocket," "shuffle through a book," "pick beads," and "pull on a glove" via oral commands. She could conduct all of these movements except for "pull on a glove" with her left hand, but she could not conduct any of these movements with her right hand. There were no problems with her right–left orientation.

Cognitive function

Cognitive function Delayed memory assessments, including the Wechsler Memory Scale–Revised (WMS–R; delayed memory index $= 92$) and RAVLT (repeated learning $= 4-6-8-12-11$, delayed learn $ing = 9/15$, showed intact ability. For language functioning, the SLTA revealed intact performance on subtests assessing repetition, pronunciation, naming objects, reading and auditory comprehension of kana and kanji letters, but she had problems with reading and auditory comprehension of short sentences as well as dictation. The token test also revealed mild auditory comprehension decline (score $= 152/165$). Although O.T. exhibited slight declines in auditory comprehension and intellectual functioning (RCPM score $= 19/36$), she was able to comprehend our instructions and complete our assessment. Cube copy, line bisection, and block construction task performance indicated significant visuospatial construction deficits, although there were no signs of unilateral neglect.

Imaging

T1-weighted MRI without contrast enhancement showed bilateral atrophy of the superior and inferior parietal lobules and the anterior parts of the superior temporal lobes, more marked for the left hemisphere. An ECD (technetium-99m-ethyl cysteinate dimer)-SPECT (single photon emission computed tomography) scan revealed blood flow reductions at the bilateral parietal cortex, basal ganglia, and thalamus (Figure 2). Neurological assessment showed Babinski reflexes, deep tendon reflexes, and mild muscle rigidity on

Figure 2. T1 density weighted image from a magnetic resonance imaging (MRI) scan and single photon emission computed tomography (SPECT) image for O.T. To view a color version of this figure, please see the online issue of the Journal.

her right side. She did not demonstrate reduced muscular force, ataxic movements, or walking and standing problems.

O.T. had clinical features consistent with corticobasal syndrome (Boeve, Lang, & Litvan, [2003\)](#page-11-0): insidious onset and progressive course, cortical dysfunction as reflected by asymmetrical apraxia, cortical sensory loss and constructional apraxia, lateralized cognitive dysfunction with relative preservation of learning and memory, asymmetric atrophy on magnetic resonance imaging, and asymmetric hypoperfusion on single photon emission computed tomography.

Control participants

The control group consisted of 10 normal elderly volunteers (5 women and 5 men) whose ages (mean $= 67.10$ years, $SD = 3.28$) and education levels (mean = 12.60 years, $SD = 2.63$) matched those of K.T. and O.T. K.T.'s and O.T.'s ages and education levels fell within the 95% confidence limits of the control group. All volunteers were right-handed Japanese speakers, had normal or corrected-tonormal hearing and vision, and had no reported neurological or psychiatric histories (Mini-Mental State Examination, MMSE, mean = 29.70 , SD = 0.95). Informed consent for participation in this study was obtained from all participants.

Materials

This experiment employed 200 action sentences. For the memorization test, we used 100 action sentences in Japanese that described situations common to everyday life and did not involve novel actions. Forty of the 100 sentences represented actions that involved manipulation of a tool (transitive; e.g., "blow up a balloon"). The other 60 sentences represented actions performed using only a person's body (intransitive; e.g., "wave goodbye"). Sentences were divided into 10 lists of 10 sentences. The ratio of transitive to intransitive action sentences was 4:6 for each list. For the recognition test, we used 100 action sentences as distractors, such that the verb in each memorized sentence was changed. For example, the sentence "Put the glass on . . . " (memorized sentence) became "Hand the glass to . . . " (distractor sentence).

Procedure

We performed the experiment using both motor and verbal conditions. The experimenter read each sentence aloud. Then, participants were required to repeat each sentence aloud to confirm that they heard the sentence correctly. For the motor condition, the participants memorized sentences by performing the action described. For the verbal condition featuring intransitive movement, the participants memorized sentences that were read aloud by the experimenter. For the verbal condition featuring transitive movement, the participants viewed the tool mentioned in each action sentence. The tools were presented at the same time as the action sentences and were placed out of the participants' view except when being presented with the corresponding sentence. Presentation duration was 10 s for each sentence. An immediate free recall test was conducted after the presentation of a list in all conditions. The experimenter asked the participant to verbally recall as many action sentences as possible for 5 min. After recall, a yes/no recognition test was conducted. In this study, one block consisted of the time span from presentation of one list to the end of the recognition test. To collect a substantial amount of data, the blocks with K.T. consisted of 10 trials for the motor condition and 10 trials for the verbal condition. O.T. received six trials for the motor condition and six trials for the verbal condition. We used the same lists as memorization stimuli in both conditions, because it is difficult to prepare more than 200 novel simple action sentences. The experiment with K.T. was conducted over periods of four and seven days, so as not to use the same list as memorization stimuli for the two conditions in a single day. Because of the presence of paralysis in K.T. and deep tendon reflexes and mild muscle rigidity in O.T., which were pronounced on the right sides of both participants, they enacted the content of each sentence using their left hands (nondominant hand) for the motor condition. The performances of K.T. and O.T. were recorded using a video camera to check the accuracy of their enactments. With regard to the action sentences in the verbal condition, we asked both participants to enact the content at the end of the experiment each day to verify that they could accurately perform the action.

Since K.T. and O.T. could not enact with their dominant hands, we used three conditions (motor condition using dominant hand, motor condition using nondominant hand, and verbal condition) to assess the healthy elderly controls, to examine the effects of using the dominant versus nondominant hand in performing the action. Control participants performed two blocks in the verbal condition and one block in each motor condition. The participants memorized the action sentences by

performing the action described using their dominant or nondominant hand depending on condition. The action sentences were presented using the same method as that employed with K.T. and O.T. Immediate free recall and yes/no recognition tests were conducted after memorizing.

Statistical analysis

To identify abnormal discrepancies in memory performance across motor and verbal conditions, we used the revised standardized difference test
(RSDT) as suggested by Crawford and $(RSDT)$ as suggested by Crawford Garthwaite ([2005\)](#page-11-0). RSDT determines whether the patient's pattern of performance meets the criteria for either classical or strong dissociation. Classical dissociation means that the patient's memory performance is significantly different from that of the control group on one of the two tasks and that the standardized difference between tasks is significantly different from that of the controls. Strong dissociation means significant differences from controls on both tasks and that the standardized difference between tasks is significantly different from that of the controls.

Additionally, we used a modified t test (Crawford & Howell, [1998](#page-11-0)) to compare each patient's memory performance with that of the control group.

RESULTS

Control group

Tables 3 and 4 show recall and recognition memory performance. We clarified features of memory performance for K.T. and O.T. through comparison of their performances with those of the healthy adult control participants. To this end,

we first examined the enactment effect for the control group. Regarding both recall and recognition (hit and false alarm, FA, ratio), there were significant differences between motor condition and verbal condition [recall ratio, $t(9) = 2.90$, $p \le$.05, $r = .70$; hit ratio, $t(9) = 3.46$, $p < .01$, $r = .76$; FA ratio, $t(9) = -3.50$, $p < 0.01$, $r = 0.76$. These results indicate that enacted encoding facilitates both recall and recognition performance across the dominant and nondominant motor conditions.

Additionally, we compared memory performance following enactments made with the dominant and nondominant hands ([Table 5\)](#page-9-0), given that O.T. and K.T. could not perform actions with their dominant hands due to either paralysis on the right side (K.T.) or Babinski reflexes, deep tendon reflexes, and mild muscle rigidity (O.T.). Paired t tests demonstrated that there were no differences in memory performance using either the dominant hand or the nondominant hand [recall, $t(9) = 0.76$, $p = .47, r = .25$; hit, $t(9) = 0.52, p = .62, r = .17$; FA, $t(9) = 0.57$, $p = .59$, $r = .19$. These results suggest that enactment by the nondominant hand did not influence memory performance. In subsequent analyses of control group memory performance, we used the nondominant hand data.

TABLE 3 Recall performance

		Recall performance		
Subject	Condition	Accuracy $(\%)$	Frequency	
K.T.	Motor	32	32/100	
	Verbal	19	19/100	
O.T.	Motor	53.33	32/60	
	Verbal	30	18/60	
Control	Motor	55	220/400	
	Verbal	41	82/200	

TABLE 4 Recognition performance

Note. $FA = false$ alarm.

TABLE 5 The memory performance of motor condition in control group by performing with handedness or nonhandedness

Type of test		Handedness	Nonhandedness
Recall proportion		53.50	56.50
Recognition	Hit	94.50	96.00
	FA	2.50	3.00

Note. In percentages. $FA = false$ alarm.

K.T.

Based on the classification of errors in apraxia (Raade, Rothi, & Heilman, [1991\)](#page-12-0), we examined precisely how K.T. was able to perform the actions described in the sentences. In the motor condition, we checked for enactment errors using video taken during the enacted encoding. For the action sentences in the verbal condition, after the recognition tests we checked whether K.T. and O.T. were capable of performing the action in each sentence accurately. Table 6 shows the type of errors and the number of times each error occurred. K.T. could not correctly perform 66% of the actions in the motor condition and 67% in the verbal condition. Content errors included perseveration and related and nonrelated movement errors. Related and nonrelated movement errors were classified as movements that were produced accurately but were not associated in content to the requested

TABLE 6 K.T.'s number of errors when performing the action described in the action sentence

Condition		Content Temporal Space		<i>Other</i>	Total
Motor Verbal	36 37	11 21	9	10	66 67

action. Temporal errors included errors in sequencing, timing, and delay. Spatial errors encompassed errors in the amplitude of the requested action, internal configuration errors such as finger/hand postural errors, external configuration errors such as difficulty orienting to the object, and movement errors such as disturbances of characteristic movements. Other errors included no response and unrecognizable responses. K.T.'s results showed that for both motor and verbal conditions, content errors were the most frequent type observed.

To examine differences in memory performance between action sentences that K.T. could enact and those that she not enact precisely due to her apraxia, chi-squared tests was conducted for the motor condition and verbal conditions. These analyses showed that there were no differences in recall performance for the motor $[\chi^2(1) = 0.14]$, $p = .71$, Cramer's $V = 0.04$] and verbal conditions $[\chi^2(1) = 0.10, p = .76,$ Cramer's $V = 0.01$. Similarly, for recognition performance (hits), there were no differences for either the motor $[\chi^2(1) = 0.04, p = .84,$ Cramer's $V = 0.02$ or the verbal condition $[\chi^2(1) = 0.26, p = .61,$ Cramer's $V = 0.05$]. Precision of enactment during the encoding phase appears to have no influence on recall and recognition performance.

Next, we conducted an RSDT to identify abnormal dissociation in K.T.'s recall performance (Figure 3A). There was no significant dissociation, $t(9) = 0.01$, $p = .99$, $r = .00$. Subsequently, modified t tests revealed that recall ratios for both the motor and verbal conditions for K.T. were worse than those of the control group [motor condition, $t(9) = -2.16$, $p < .03$, one-tailed, $r = .59$; verbal condition, $t(9) = -2.17$, $p < .03$, one-tailed, $r = .59$. These analyses indicate that there was memory enhancement through enactment for K.T., but that K.T.'s overall recall performance was worse than that of the control group in both conditions.

Figure 3. Scatterplot illustrating memory performance. A. recall; B. hit ratio in recognition; C. false alarm (FA) ratio, in recognition of motor and verbal conditions. Red circles show K.T.'s performance, and green squares show O.T.'s performance. Individual values of controls are shown by open diamonds. To view a color version of this figure, please see the online issue of the Journal.

We also analyzed hit and FA ratios for recognition ([Figure 3B,](#page-9-0) [Figure 3C](#page-9-0)). For hit ratio, an RSDT showed a significant dissociation, $t(9)$ = 2.38, $p < .05$, $r = .62$. Modified t tests revealed that hit ratios for both the motor and verbal conditions for K.T. were far worse than those for the control group [motor condition, $t(9) = -6.02$, $p \leq .0001$, one-tailed, $r = .90$; verbal condition, $t(9) = -2.72, p < .05$, one-tailed, $r = .67$. These results indicate a strong dissociation and that there was no enactment effect for K.T.; additionally, the hit ratio for K.T. was significantly worse than that for the control group. We found no significant dissociation for false-alarm ratios, $t(9) = 0.91$, $p = .39$, $r = .29$, and no significant differences between K.T. and the control group for both conditions [motor condition, $t(9) = 0.71$, $p = .25$, onetailed, $r = .23$; verbal condition, $t(9) = -0.17$, $p =$.44, one-tailed, $r = .06$. Motor encoding appeared to decrease FAs for K.T., and there was no difference between K.T. and the control group on this measure.

O.T.

O.T. was able to enact all of the prescribed movements but exhibited consistent limb motor errors (slowness, clumsiness, and disturbances of timing) during all enactments.

We conducted RSDTs on recall, hit rate, and FA ratio for O.T., as was done for K.T. ([Figure 3](#page-9-0)). There were no significant dissociations [recall, $t(9) = 0.47, p = .65, r = .16$; hit, $t(9) = 0.67, p =$.50, $r = .22$; FA, $t(9) = 0.15$, $p = .89$, $r = .29$]. Comparison of O.T.'s memory performance to that of the control group using modified t tests did not show any significant differences across conditions. These results imply that, for both recall and recognition, O.T. did not show memory decline under either motor or verbal conditions, and that the enactment effect was observed for her as well as for the control group.

DISCUSSION

Several researchers have suggested that an important factor in episodic memory enhancement through motor encoding is the derivation of physical motor information (speed, form, and amplitude of a movement) derived from performing actions (e.g., Engelkamp, [1998](#page-11-0)). This view has been supported by functional brain imaging studies showing reactivation of the motor cortex during retrieval following enacted encoding (Nilsson et al., [2000](#page-12-0); Nyberg et al., [2001](#page-12-0); Masumoto et al.,

[2006\)](#page-12-0). Brain research using fMRI (Russ et al., [2003\)](#page-12-0) has reported that activities in the bilateral inferior parietal cortex (supramarginal gyrus; Brodmann area 40) are associated with movement representation that increases during motor encoding, which suggests that the enactment effect depends on higher cognitive processes. Thus, we attempted to examine the role of movement representation on the enactment effect by focusing on two patients with apraxia: K.T., who had multiple movement representation deficits, and O.T., who could not gain feedback regarding correct physical motor information from enactment on account of clumsiness and awkwardness.

K.T. could perform only about 35% of the actions in the motor condition because of her apraxia. If movement representation is involved in the enactment effect, this should be reflected in a corresponding decline of memory performance in the motor condition. Results showed that the enactment effect did occur for K.T. during recall. As has been previously reported, when engaged in a recall task, visual, tactile, and physical motor information derived from enacted encoding are factors that contribute to the enactment effect (Nilsson et al., [2000](#page-12-0); Nyberg et al., [2001](#page-12-0)). Our results suggest that recall performance is indeed enhanced by these factors rather than by movement representation. However, there was no enactment effect for recognition, although a previous study found that the enactment effect is robust and more pronounced during recognition than during recall (Mohr, Engelkamp, & Zimmer, [1989](#page-12-0)). Concerning this curious absence, the recognition task used in this study likely depended on cognitive processes associated with movement representation. To perform the recognition task, the participants must identify and make judgments based on previous identifications (Mandler, [1980](#page-12-0)). In our recognition task, we used distractor sentences in which the verbs were changed. This task required participants to perform three identifications in the motor condition: the action sentence presented at encoding (episodic memory for the action sentence), the action enacted at encoding (episodic memory for the action), and the action sentence presented at recognition (conceptual knowledge or semantic memory for the action). The fact that K.T.'s FA ratio was not different from those of the control group and O.T. implies that K.T. had intact conceptual knowledge and episodic memory for the action sentences. Additionally, K.T. showed a significant enactment effect for recall, further indicating that she had intact episodic memory for the action sentences. However, it would appear that mismatch between episodic memory for action (action enacted at encoding) and conceptual knowledge for action (action presented at recognition), which were derived from her movement representation deficits, could underlie the absence of an enactment effect on recognition (hit rates). The parietal cortex is associated with mental images of movement (Buxbaum et al., 2005; Sirigu et al., [1996\)](#page-12-0). Movement representation, which is an implicit process, can be made conscious through motor imagery (Jeannerod, [1995](#page-12-0)), and Masumoto et al. ([2006\)](#page-12-0) suggested that the action enacted at encoding is retrieved as mental images of movement at recognition. Additionally, Kalénine, Buxbaum, and Coslett ([2010\)](#page-12-0) conducted semantic and spatial action recognition tasks for 43 left-hemisphere stroke patients and reported that the inferior parietal lobule is critical for encoding object-related postures and movements. Results for K.T. suggest that movement representation is an important factor in recognition that requires individuals to identify enacted actions at encoding and to match episodic memory of such actions and conceptual knowledge of action.

For patient O.T., who had corticobasal syndrome, the enactment effect was observed for both recall and recognition. Jacobs et al. (1999) reported that corticobasal syndrome patients performed relatively well on a gesture-discrimination task and showed an ability to recall and recognize gestures. For motor condition retrievals, Masumoto et al. [\(2006](#page-12-0)) suggested that the enactment effect occurs through the reactivation of the physical motor information within the primary motor cortex. Subsequently, this information is transmitted to the parietal cortex, which controls higher brain function and facilitates nonverbal retrieval processing activities such as movement representation. Our findings for O.T. indicate that even if enactment of actions is slow, clumsy, or performed with disturbed timing because of dysfunctional innervation patterns, the physical motor information obtained from the enactment works to facilitate the retrieval process.

Although this study was the first to examine the enactment effect in patients with apraxia, it has certain limitations. We could not examine the involvement of movement representation in detail. Further studies are necessary to separately examine spatial representations, knowledge of manipulation related tool and body-part, and mental images of movement. Additionally, K.T.'s overall memory performance in this experiment was inferior to that of O.T. and the control participants regardless of recall or recognition, though neuropsychological memory tests [\(Table 2](#page-5-0)) showed that K.T.'s scores

were slightly better than O.T.'s. These results suggest the possibility that patients with apraxia derived from dysfunctions of movement representation show poor episodic memory for action. This association between movement representation and memory for action also warrants further consideration.

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