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Stimulus Equivalence and Brain Function in Broca's Area: A NIRS Study.

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I. Introduction

Equivalence relations or stimulus equivalence (Sidman, 1994, 2000; Sidman & Tailby, 1982) is defined as a derived relational response without direct training developed through a series of interrelated conditional discriminations. This is demonstrated, for example, when a person is trained to choose stimulus B in the presence of stimulus A and to choose stimulus C in the presence of stimulus B. After training, most people can complete an untrained relation such as choosing A in the presence of B (symmetry), choosing B in the presence of C (symmetry), choosing C in the presence of A (transitivity), and choosing A in the presence of C (transitivity or equivalence). The phenomenon of equivalence relations or stimulus equivalence has been reported in several populations, including children (Saunders, Drake, & Spradlin, 1999), children with developmental disabilities (Yamamoto & Shimizu, 2001).

Recently, some researchers have suggested that equivalence relations are established by functional learning in a verbal community or through an ontogenetic process. Lowe et al. (Dugdale & Lowe, 1990; Horne & Lowe, 1996) argued that the function of naming is based on equivalence relations. In this case, naming behavior means not only naming the materials, but

also the bidirectional relation between the material and the name (Dugdale & Lowe, 1990).

Dickins et al. (2001) tried to clarify this naming problem by neurological research. Using functional MRI (fMRI), they evaluated brain activation while 12 participants were trained in the relations of pictorial stimuli in a matching-to-sample (MTS) task. Participants who showed derived relations activated three areas: the left dorsolateral prefrontal cortex (DLPFC), the left Brodmann area 10 (BA 10), and the left caudate. Participants who failed to acquire equivalence relations activated DLPFC and BA10 bilaterally. Dickins et al. compared these data with results of a verbal fluency (VF) task, which evaluated the number of words the participant could say which matched a particular condition.

In previous studies, this task had activated DLPFC and Broca's area. In Dickins et al.'s fMRI data, the VF task activated Broca's area, but the MTS task did not. This result suggests that brain activation during equivalence relations was not associated with the simple sub-vocal articulation of stimulus names.

Dickins et al. (2001) evaluated brain activation after training. In this study, we assessed whether participants showed a difference in the change of oxygenated hemoglobin in the interior frontal gyrus (IFG) including Broca's area for the derived relations of identity matching, symmetry, and transitivity during training, before training, and after training.

II. Methods

1. Participants

Thirteen healthy, right-handed participants (mean age $22 \pm \text{SD} = 3.21$, 19 to 30 years old; 5 males and 8 females) volunteered. Written informed consent was obtained from all participants. This study and protocol were approved by the ethics committee of the Faculty of Literature of Keio University (No. 04001).

Table 1. Relations and stimuli.

Relation	Sample	Comparison			1	2	3	4
		correct	incorrect					
Symmetry	B1	A1	A2	A				
	B2	A2	A1					
	C1	B1	B2					
	C2	B2	B1					
Transitivity	A1	C1	C2	C				
	A2	C2	C1					
Equivalence	C1	A1	A2	D				
	C2	A2	A1					
Identity	D1	D1	D2	D				
	D2	D2	D1					
	D3	D3	D4					
	D4	D4	D3					

Figure 1. Stimulus sets (10 Stimuli / 4 stimulus sets).

2. Stimulus sets

Ten nonsense visual stimuli were used. Each stimulus consisted of 8 or 9 squares placed in a 6 x 3 matrix of voxels (Critchfield & Perone, 1990; Suzui, Kuwahara, & Okouchi, 2007). Six stimuli were assigned to classes A, B, or C (two in each class) and four stimuli were assigned to class D randomly (see Figure 1). We used to the training about A1-B1, A2-B2, B1-C1, and B2-C2 relation. In the test, we assessed four symmetries (B1-A1, B2-A2, C1-B1, and C-B2), two transivities (A1-C1 and A2-C2), two equivalences (C1-A1 and C2- A2), and four identities (D1-D1, D2-D2, D3-D3, D4-D4).

3. Near-infrared spectroscopy (NIRS) settings

Brain activation indicated by change of oxy-hemoglobin was measured by the NIRS system (ETG-7000, Hitachi medico) for all participants. The NIRS system consists of 8 near-infrared light units (785 and 830 nm) and 8 detector units and measures cortical changes in oxygenated hemoglobin (oxy-Hb), deoxygenated hemoglobin (deoxy-Hb), and total hemoglobin

(total-Hb). Each light unit and detector unit was assigned to 3×5 probes (height 6 cm and width 12 cm) and the inter-light and detector distance was set to 3.0 cm. The probe was fixed on the left side of the head by a custom headband and covered the frontal and temporal areas. The probe at the second vertical row was set in the T3-Cz line according to the international 10-20 method (Okamoto et al., 2004; see Figure 2).

4. Verbal fluency (VF) task

In the Verbal Fluency (VF) task, the participant was required to generate as many words as possible. For example, a participant might be instructed to “generate words which are spelled with ‘a’ as the first letter.” In this task, the participant was required to say the words covertly, not overtly (i.e., not aloud). The VF task consisted of a 20 sec stimulus period followed by a 20 sec rest period. The VF task was repeated three times.

5. Matching to sample (MTS) task

The MTS task was presented twice, before the training (pre-assessment) and after the Training (post assessments). The participants sat on a chair in front of a desk. An 18-inch computer monitor and a keyboard were placed on the desktop. The participant wore the NIRS probe during the MTS task. Before the experiment, we read the following instructions: “In this task, three visual stimuli will be presented in the computer display. The stimulus in the upper part is the sample stimulus and the two stimuli in the lower part are the comparison stimuli. Please choose the comparison stimulus which you think matches the sample stimulus. If you choose the right stimulus, you will press the right arrow key. If you choose the left stimulus, you will press the left arrow key. Each trial has a time limit. The next trial will start if you do not push the arrow key within 5 seconds. When the cross-shaped symbol is presented, fixate on the symbol.”

Figure 3 depicts a sample display of the MTS task, including the sample stimulus and two comparison stimuli. First, the sample stimulus was presented in the upper part of the display and two comparison stimuli were presented in the lower part of the display. The participant was required to push the left or right arrow key corresponding to the position of

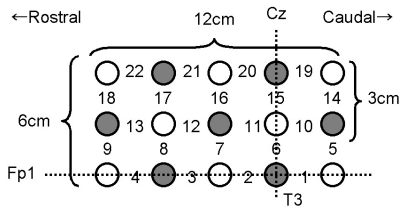


Figure 2. NIRS probe setting.

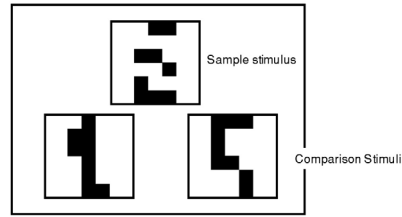


Figure 3. Sample display for MTS and Training task.

the selected comparison stimulus. After the participant pressed the left or right arrow key or five seconds had passed, the next trial began. The participant was not given feedback on whether responses were correct or incorrect during the MTS task.

The MTS task consisted of a 30 sec period of 4 trials, followed by a 20 sec rest period. The MTS task was repeated eight times. Each period of the MTS task included the relations of symmetry, transitivity, equivalence, or identity, with each relation presented twice. The number of correct responses was measured.

6. Training task

The Training task followed almost the same procedure as the MTS task. We trained four relations: A1-B1, A2-B2, B1-C1, and B2-C2. In the Training task, the participant was given feedback on whether responses were correct or incorrect. A red circle was displayed when the participant provided a correct response; no graphic was presented following an incorrect response. The Training task consisted of a 30 sec period of 4 trials, followed by a 20 sec rest period. The Training task was repeated 10 times in the one measurement of NIRS. The number of correct responses was measured, and the Training task was repeated until the participant provided eight correct responses on eight consecutive trials as two blocks. When the participant showed eight correct responses while one measurement of NIRS, we transferred to post assessment phase.

III. Results

1. Change of oxy-hemoglobin during the VF task

Figure 4 shows the change of oxy-Hb level during the VF task. We assumed that the increase in the oxy-Hb (mMol / mm) level in the cortical area was task-related, because the oxy-Hb level is sensitive to brain activities (Suzuki et al., 2004; Hatakenaka, Miyai, Mihara, Sakoda, & Kubota, 2007). We used z-scores to compare the inter-participant differences in increased oxy-Hb. The z-scores were calculated by subtracting the mean oxy-Hb level for 5 sec before the task period from the mean oxy-Hb level for 3 to 8 sec during the task, and then dividing this difference by the standard deviation of the oxy-Hb level for 5 sec before the task period. We rejected trials that included large body movements or noise. In previous study (Dickins et al., 2001), Broca's area mostly activated while VF task. We decided that channel 3 represented Broca's area, because oxy-Hb level increased in this channel while the VF task.

2. MTS task performance

We cut off the relations were under 0.80 in the post assessment, from the mean correct response and re-calculated the average of correct response rates in the pre- and post-assessments. These are shown in Figure 5. In the pre-assessment, the average of correct response rates for symmetry, transitivity, and equivalence were 0.50 (SD = 0.19), 0.39 (SD = 0.27), and 0.48 (SD = 0.18), respectively. All relations were approximately at chance levels (0.50). Identity was 0.95 (SD = 0.11). In the post-assessment, the average of mean correct response rates for symmetry, transitivity, and equivalence were 0.95 (SD = 0.06, n = 8), 0.96 (SD = 0.06, n = 7), and 0.98 (SD = 0.05, n = 6), respectively. Identity was 0.97 (SD = 0.05, n = 13).

3. Change of oxy-hemoglobin during the MTS task

We cut off the period of oxy-Hb data that were under the 0.80 correct response rate of MTS task in the post assessment. Then, we compared the differences in increased oxy-Hb in channel 3 for each relation. We rejected

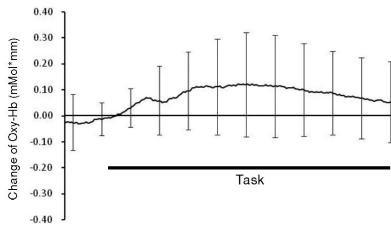


Figure 4. Change of Oxy-Hb during VF task.

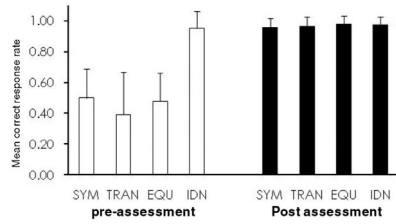


Figure 5. Mean correct response rate in Pre and Post-assessment (established derived relation only).

trials that included large body movements or noise. The average changes of oxy-Hb level for 5 to 10 sec in the MTS and VF tasks are presented in Figure 6. Symmetry and transitivity produced negative activation levels, -0.05 (SD = 0.01) and -0.02 (SD = 0.01), respectively. Among the derived relations, only equivalence produced a positive level, with a mean of 0.03 (SD = 0.01). Identity showed no activation, with a mean of 0.00 (SD = 0.01). The highest mean was for the VF task, 0.11 (SD = 0.01).

The changes in oxy-Hb levels were analyzed by a one-way analysis of variance (ANOVA). The main effect ($F(4, 245) = 1826.35, p < .001$) was significant. We used Tukey's multiple comparison tests to evaluate the differences between the VF task and each relation in the MTS task. We found significant differences ($p < .05$) between the VF task and symmetry, transitivity, equivalence, and identity.

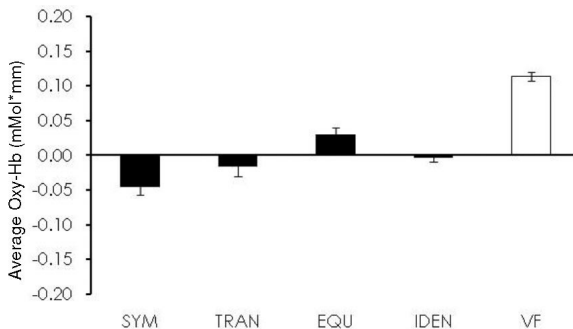


Figure 6. Average Oxy-Hb in Post-assessment (established derived relation only) and VF task.

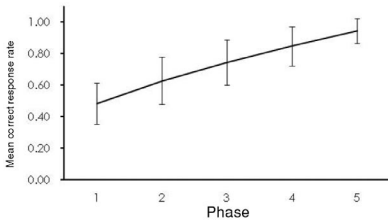


Figure 7. Mean correct response rate in Training task.

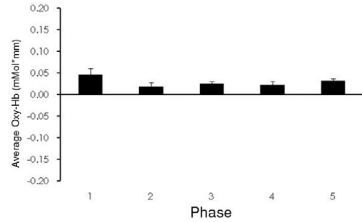


Figure 8. Average Oxy-Hb in Training task.

4. Training task performance

The mean number of trials presented during training was 95.38 (SD = 30.72). Participants trained from 10, 20, or 30 period of four trials. We calculated the average correct response rates over five phases, as shown in Figure 7. Each phase was average score which consisted of two to six period of four trials. The average correct response rates for the five phases were 0.48 (SD = 0.13), 0.63 (SD = 0.15), 0.74 (SD = 0.14), 0.85 (SD = 0.13), and 0.94 (SD = 0.08). The correct response rates gradually increased, passing the learning criterion during the fourth phase.

5. Change of oxy-hemoglobin during the Training task

We compared the differences in the increase of oxy-Hb in channel 3 during the training process. We rejected trials that included large body movements or noise. Figure 8 presents the average changes of oxy-Hb levels for 5 to 10 sec in the Training task. The average changes of oxy-Hb level in the five periods were 0.05 (SD = 0.01), 0.02 (SD = 0.01), 0.03 (SD = 0.01), 0.02 (SD = 0.01), and 0.03 (SD = 0.01). The change of oxy-Hb levels did not show either upward or downward trends.

IV. Discussion

In this study, we assessed whether or not participants showed differences in the change of oxygenated hemoglobin for the relations of identity matching, symmetry, and transitivity on the interior frontal gyrus including

Broca's area. We found that the change of oxygenated hemoglobin level in Broca's area was lower for the VF task than for evaluation of derived relations, including identity, in the post-assessment. This means that an overt stimulus naming response did not occur when the participants showed an equivalence relation. This confirms the findings of a previous study (Dickins, et al., 2001).

Eikeseth and Smith (1992) showed that participants who failed to acquire equivalence relations were able to demonstrate derived relations after they were trained to name stimuli which were in the same class. Horne and Lowe (1996) pointed out that naming is based on equivalence relations. In the present study, participants did not name the stimuli covertly.

Dickson et al. (2001) used graphical icons in their study. They assumed that those stimuli could be easily named, although the participants were not asked to name them covertly or overtly. It is possible that participants named the stimuli when it was difficult for them to learn the relations. The present study used complex, nonsense visual stimuli, and participants needed approximately 100 trials to learn only four relations. In the training phase, the change of oxygenated hemoglobin level in Broca's area was low. No activation in Broca's area occurred when participants were learning the stimulus-stimulus relations. This indicates that participants did not overtly name the visual stimuli during the acquisition of trained relation.

The lack of activation in Broca's area also indicates that no covert naming response occurred in the MTS or training tasks. These results suggest that naming may have facilitated the establishment of equivalence relations, but naming was not an essential qualification.

In future research, we expect to evaluate other cortical areas which were activated during the MTS or VF tasks in a previous study (Dickins et al., 2001); for example, the bilateral DLPFC, superior temporal sulcus (STS), and inferior frontal sulcus (IFS). By doing so, we hope to clarify the basis of equivalence relations from the viewpoint of brain function.

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