

The cerebral basis for language learner strategies: A near-infrared spectroscopy study

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Abstract

In this paper, we validate Macaro's (2006) model of strategy use among language learners by assessing the amount of neural activity around the prefrontal cortex, the supposed locus of working memory (WM). We also examine whether WM activation during first language (L1) strategy deployment is lower than WM activation during second language (L2) strategy deployment, as predicted by Macaro's model. In the analysis, we consider data obtained through an innovative neuroimaging technique (near-infrared spectroscopy) and stimulated-recall interviews. The results reveal greater brain activity during execution of the L1 and L2 tasks than in a control condition; further, use of strategies in the L2 resulted in stronger WM activation than use of strategies in the L1. These results provide partial support for the validity of Macaro's model.

Keywords: brain imaging; learner strategy; working memory; reading strategy; Macaro's framework

Research on language learner strategies (henceforth "strategies") has been ongoing for over 30 years, during which many theoretical and empirical efforts have been made. Strategy research has firmly established itself in the field of second-language acquisition (for reviews, see Grenfell & Macaro, 2007; Griffiths, 2008; Oxford, 2011; Takeuchi, Griffiths, & Coyle, 2007). The application of strategy-research findings to pedagogical purposes (i.e., strategy instruction) began as early as the end of the 1980s, and some positive results of such applications have been reported (Goh & Taib, 2006; Graham & Macaro, 2008; Ikeda, 2007; Macaro & Erler, 2008; Mizumoto & Takeuchi, 2009; O'Malley & Chamot, 1990; Ozeki, 2000; among others).

Nevertheless, several researchers have indicated that strategy research has some troublesome features. For example, Rees-Miller (1993, 1994) argued that most strategy research lacked a solid theoretical framework. Gu (1996), along with Swan (2008), elucidated several problems inherent in the existing definitions of "strategy," most of which had taxonomic deficiencies. McDonough (1999) also stressed the lack of adequate foundational theories for strategy research and argued in support of "the need for theoretical research to develop precision in our conception

of strategies” (p. 14).

Theoretical Framework of Learner Strategies

After having criticized strategy research for its paucity of theoretical underpinnings, Dörnyei (2005), along with his colleagues (Tseng, Dörnyei, & Schmitt, 2006), recently suggested a re-conceptualization of “strategies” within the self-regulatory paradigm of the field of educational psychology. In doing so, they hoped to solve several persistent problems in the field of strategy research.¹ Self-regulation refers to the degree to which individual learners are active participants in their own learning processes. Self-regulation is a more dynamic concept than learner strategies, as it highlights learners’ strategic efforts to manage their own achievement through specific beliefs and processes. It is also a multidimensional construct, including cognitive, metacognitive, and emotional processes (of which the use of learner strategies is only one), that learners can apply to enhance their academic achievement (Dörnyei, 2005). In Dörnyei’s framework, the use of strategy is associated with goal-oriented activity. By setting goals, learners establish reference points for continuous self-evaluation. Goal setting also helps learners to select and implement strategies by anchoring strategy use within a specific context related to the established goal. Gao (2007) and Manchón (2008) rightly indicated that replacing “strategies” with a “self-regulating mechanism” helps to address the main concerns raised by several studies, though they admitted that this replacement does not entirely nullify the vagueness and lack of comprehensiveness inherent in the construct of strategies (for a review, see Grenfell & Macaro, 2007).

Another theoretical framework stimulated by Dörnyei’s (2005) attempt was recently proposed by Macaro (2006). Macaro’s framework had its basis in cerebral activities and is thus testable by using brain-imaging techniques. Rooted in an information-processing view often associated with cognitive psychology, Macaro’s framework adopted a triple-layered construct with the following three facets: strategies, processes, and skills. As does Dörnyei’s theorization, Macaro’s framework emphasized the goal-oriented nature of strategy use.² He noted that goals for strategy use can be self-imposed or other-imposed. For example, in educational settings, learners sometimes set goals for themselves, but at other times, teachers (or others) do so for learners (Macaro, 2006; Manchón, 2008). Macaro thus argued that goal orientation is an important feature of strategy use, and he defined strategies as conscious mental actions, which are directed towards the achievement of a particular goal in a particular situation.

To enumerate the distinction between conscious strategies and subconscious activities in the brain, Macaro (2006) drew from Baddeley’s (1986, 1997) model of working memory (WM).³ He contended that “learner strategy is located in [WM]” (Macaro, 2006, p. 327) and that attention, or consciousness, is important to its activation; thus, strategies represent mental actions undertaken with specific goals and evaluated against situations in which learning occurs. On the other hand, learning processes are made up of cognitive and metacognitive strategies. The strategies operate in clusters and “become L2 processes... in relation to language tasks” (Macaro, 2006, p. 332). Macaro further argued that through the repeated, successful activation of L2 processes during specific tasks, measurable and observable language skills develop and thus result in L2 learning.

Macaro's (2006) framework posited that strategies, which originate in WM, play an integral role in successful L2 learning. He contended that they are "the raw material without which L2 learning cannot take place" (p. 332). He indicated, however, that "[strategies] are not unique to L2 learning" (p. 330). Deployment of strategies is often observed even when we solve a particular task in the L1 (e.g., reading articles, listening to lectures). In fact, Nambiar (2009) reported the possibility of cross-linguistic transferability of reading strategies. This possibility emerged because the definition of "strategies" in Macaro's (2006) framework was conscious mental actions that are directed towards the achievement of a particular goal in a particular situation, which is applicable to the task-solving activities in the L1. We assume, however, that the levels of WM activation differ between strategy deployment in the L1 and L2, especially when the L1 and L2 are linguistically different, as in the case of Japanese and English. Considering that "strateg[ies] will [have] different levels of automaticity" (Macaro, 2006, p. 329), WM activation might be much lower in L1 task-solving activities than in activities of the same nature in the L2 (Stowe & Sabourin, 2005).

While Macaro's framework (2006) provided much-needed theoretical underpinnings for learner strategy research, its validity has not been empirically tested. Therefore, in this research, we used a neuroimaging technique called Near-Infrared Spectroscopy (NIRS) to validate Macaro's framework by assessing the amount of neural activity in brain areas that correspond to the supposed locations of WM. In the next section, we review the findings of brain-imaging studies and describe the functions and supposed anatomical localization of WM, which forms the basis of Macaro's framework.

Functions and Locations of WM

Baddeley's WM model (1997), on which Macaro's (2006) framework was based, had three components: (a) the central executive, (b) the phonological loop, and (c) the visuo-spatial sketchpad. The central executive plays the most important role as a controlling attentional system, supervising and coordinating the two subsidiary slave systems,⁴ the phonological loop and the visuo-spatial sketchpad. The phonological loop has two functions: it provides temporary storage of phonological information, and it executes articulatory rehearsal, which assists in retention of the phonological information. The visuo-spatial sketchpad retains visually or spatially coded information.

A large number of brain-imaging studies have investigated the anatomical locations corresponding to these three components of WM (e.g., Cabeza & Kingstone, 2006). The previous studies have generally supported the view that the prefrontal cortex (PFC) is responsible for the functioning of WM (e.g., Curtis & D'Esposito, 2003). However, a few studies have suggested that the location of WM is not limited to one area of the PFC. For example, Goldman-Rakic (1996), who first described the relationship between WM and the PFC, suggested that WM is domain-specific: There may be multiple domains of WM in which different parts of the PFC process and store visuo-spatial information, object features, and verbal information. Other researchers (e.g., Owen, Evans, & Petrides, 1996) supported the view that WM is process-specific: the ventrolateral prefrontal cortex (VLPFC) (Brodmann areas [BA] 45 and 47) stores or maintains information, whereas the dorsolateral prefrontal cortex (DLPFC) (BA 9 and 46)

manipulates or monitors information (See Figure 1).

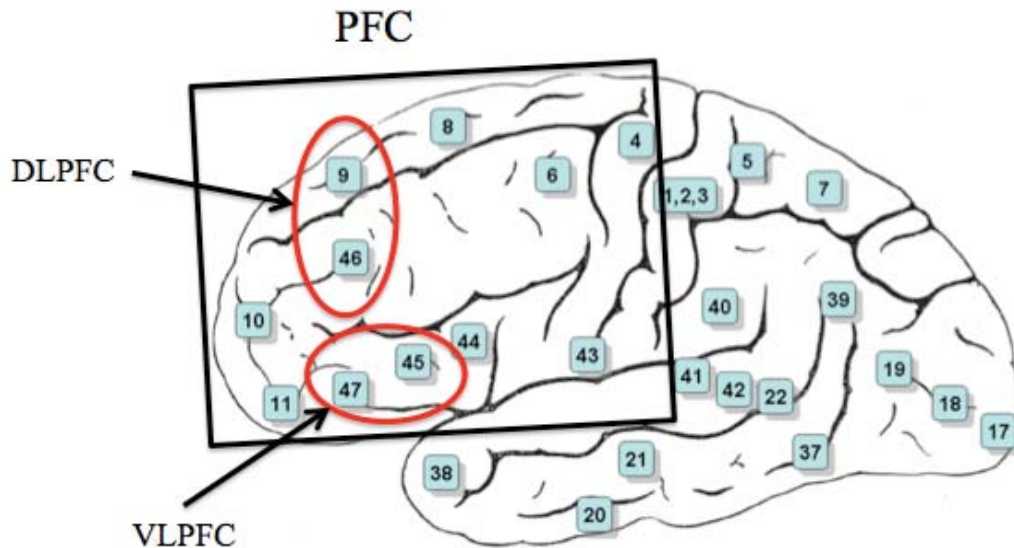


Figure 1. Lateral surface of the brain with Brodmann areas numbered.
Retrieved from <http://en.wikipedia.org/wiki/File:Gray726-Brodman.png>

Other research on WM has shown that it is more diffusely organized in networks that cover larger areas of the brain. Fuster (2005), for example, viewed WM as “active memory” (p. 155) that is essentially analogous to short- and long-term memory. In Fuster’s view, WM is thus “updated long-term memory” for processing the information at hand. As such, WM shares cortical networks with short-term and long-term memory, and its function consists of “neural transactions within and between these networks” (Fuster, 2006, p. 125). Fuster postulated that executive memory networks reside mainly in the frontal cortex, while perceptual memory networks are located mostly in the posterior cortex. At the same time, all memory networks are densely distributed in the cortex, and they interact with and overlap one another. Thus, a neuron can exist anywhere in the cortex, and so can a memory stored in WM. This perspective is somewhat different from the “localizationist” view mentioned above.

A growing number of brain-imaging studies support a dynamic and distributed view of WM and the view that its basic functions are localized in the PFC (e.g., Cabeza & Nyberg, 1997; Carpenter, Just, & Reichle, 2000; Kane & Engle, 2002; Smith & Jonides, 1998; Wager & Smith, 2003; among others). Nevertheless, a few studies have challenged the general view that the locus of WM is in the PFC. Investigating WM storage of human faces, Postle, Druzgal, and D’Esposito (2003) reported that no part of the PFC stored information about the observation of faces; instead, they found that the posterior cortex was activated. Another study by Zurovski et al. (2002) investigated spatial and phonological information in WM. Although they found robust activation within the left inferior gyrus in response to WM activation (BA 44 and 45), they concluded that “no region specific to phonological WM was found” (p. 45).

The above-mentioned studies indicate that no conclusive evidence exists regarding the precise

anatomical localization of WM. All that can be asserted with certainty is that WM resides in several places in the brain (Osaka, 2000) and that the PFC is the main area of increased activity when WM is activated (Beardsley, 1997; Osaka, Logie, & D'Esposito, 2007). D'Esposito's (2007) recent review of the neural mechanisms of WM supports this view: "WM is not localized to a single brain region but probably is an emergent property of the functional interactions between the PFC and the rest of the brain" (p. 761). For this reason, the current study focused on activity in the PFC to measure WM performance.

The Study

Aims of the Study

In this study, we tested two research questions by applying Near-Infrared Spectroscopy (NIRS), a non-invasive measurement of the activation of the cerebral cortex, to participants as they read L1 and L2 texts of comparable difficulty levels:

- 1) Is the purported location of strategies (i.e., activation of WM during the strategy deployment) empirically supportable?
- 2) Is the activation of WM in L1 strategy deployment significantly lower than that in L2 strategy deployment, as expected on the basis of Macaro's (2006) framework?

Target Strategies

We postulated that investigation of reading-strategy use is the most suitable method by which to test Macaro's (2006) framework because reading-strategy use is said to elicit the perceiving, holding, processing, and encoding functions of WM. Early studies on reading strategies began with description and classification of successful readers' deployment of strategies (e.g., Hosenfeld, 1976, 1977). Other attempts at identifying the use of strategies based on the psycholinguistic view of reading often reported that more successful readers used more top-down or global strategies than did less successful ones (e.g., Barnet, 1988; Block, 1986; Carrell, 1985, 1989; Papalia, 1987; among others). However, later studies found that the balanced use of both top-down and bottom-up strategies is important and that the timing, manner, and monitoring of strategy use play an important role in successful reading (Anderson, 1991; Macaro, 2001; Swan, 2008).

Recently, investigations of the relationship between reading-strategy use and WM have begun (e.g., Carretti, Borella, Cornoldi, & De Beni, 2009; Osaka, 2002; Savage, Lavers, & Pillay, 2007; Walter, 2004; Yoshida, 2003) because the use of reading strategies is said to forcefully elicit the basic functions of WM (Macaro, 2006). Since some of the aforementioned studies indicated the possibility of a relationship between reading strategies and WM, we postulated that it is suitable to focus on the use of reading strategies to empirically test Macaro's (2006) framework, in which the interplay between WM and strategy use plays an integral part.

Operational Definition of “Strategies” in this Study

The provision of an operational definition of “strategies” before a full description of the study is in order, especially as many studies on strategies have been criticized for the ambiguous nature of their definitions of this key concept. In this study, following the definition proposed by Macaro (2006) and Manchón (2008), “strategies” are defined as mental actions taken in the service of immediate, other-imposed goals, which are pursued in L1 or L2 reading tasks. The phrase “other-imposed” is inserted into the definition because the goals in this study are imposed by the researchers.

Method

Participants

Twelve right-handed, healthy volunteers participated in the study. We chose right-handed individuals because it is known that handedness affects the functioning of the brain. All of the participants were Japanese English as a Foreign Language (EFL) learners (nine women and three men) with mean TOEIC[®] scores of 936.79 ($SD = 57.13$).⁵ We selected participants with high reading proficiency because they need to be well versed in using the target strategies employed in the current study. The participants’ ages ranged from 23 to 50 (mean 39.36) years. All participants, except one (who was a graduate student in a Teachers of English to Speakers of Other Languages [TESOL] Master of Arts [MA] program), were experienced EFL instructors who had taught at a variety of institutions.

Written informed consent was obtained from the participants after they were given a complete description of the experimental procedures and the purpose of the study. They also completed a biographical information questionnaire, which asked questions such as their age and L2 study background. Each participant was given a bookstore gift certificate (valued at 1,000 Japanese Yen [approximately US\$10]), as a token of our appreciation for their participation in the study. All the procedures in the study followed the principles of the Declaration of Helsinki (World Medical Association, 2008).

Tasks

The participants were asked to read three passages during three different reading tasks (one passage for each task). Of the three tasks, one demanded normal reading (i.e., reading without any particular goal or conscious application of any specific cognitive strategies), which served as a control for the other two conditions. In the two other reading-task conditions, the participants were asked to consciously use specific reading strategies while reading. The specific reading strategy was either (a) scanning or (b) finding the topic sentences, each of which has been regarded as a distinct reading strategy (Barnett, 1988; Ikeda, 2007; Macaro, 2001; McDonough & Chaikitmongkol, 2007)

We assumed that both of these experimental tasks would be able to elicit the perceiving, holding, processing, and encoding functions of WM (Macaro, 2006) and that the task load would be

manageable for our participants. We prepared two types of experimental tasks in order to arrive at more generalizable findings: as the two types of experimental tasks require different strategies, we assume that other strategies that are consciously employed during reading may also activate the brain regions corresponding to WM.

We prepared passages for each of the three types of reading tasks in the participants' L1 (Japanese) and L2 (English) (six in total). The appropriateness of all reading passages and tasks, including such aspects as topic choice and difficulty, was ascertained through a pilot study with other groups of learners having similar proficiency levels. Table 1 summarizes the reading passages used in the study. The readability indices in Table 1 demonstrate that the difficulty levels of the passages within each language group were confirmed to be similar.⁶

Table 1. *Summary of the Reading Passages*

Language	Task	Time (seconds)	Topic	Length (words)	Readability
Japanese (L1)	Normal Reading	60	Difference between PR and Ads	1,181	9.0
	Scanning	240	Environmental Problems	1,618	11.0
	Finding Topic Sentences	240	Winny: information divulging	1,618	10.0
English (L2)	Normal Reading	60	Suicide in Japan	2,534	12.0
	Scanning	240	Push-button Medicine	2,199	12.0
	Finding Topic Sentences	240	Women dental health	1,862	12.0

Note. The readability indices of the English passages were measured in terms of Flesch-Kincaid Grade Levels, and those of the Japanese passages were measured with the Automatic Assessment of Japanese Text Readability (Sato, Matsumoto, & Kondo, 2008). The duration of the normal reading task in each language was shorter than those of the other two tasks. This shortness did not affect the results because measurements across all tasks were averaged for analyses: 60 seconds was sufficient to provide representative data on participants' normal-reading skills.

The scanning task required the participants to scan a passage and answer three attached true-or-false (T/F) questions. The finding-the-topic-sentences task required participants to underline the topic sentences of each paragraph and then write a summary of the passage in either their L1 or L2. The requirements to answer the T/F questions and summarize the passage were added in order to ensure that the participants engaged in reading tasks, which require mental actions to be taken in the pursuit of immediate goals, as outlined in the definition of reading strategies in the current study.

Procedures

The study was conducted in a quiet room. Each participant sat in a chair and a task sheet attached

to an adjustable plastic holder was placed on the desk in front of the participant. Prior to the experiment, participants were provided with both a detailed explanation of each task and the opportunity to undergo a training session. Using sample reading passages, they were shown how they should employ the designated strategies and complete the tasks. For the control condition, the participants were instructed not to read strategically.

In all three tasks, the participant was asked to read the passages with their index finger pointing at the place where their eyes were fixated; this enabled us to ascertain the approximate places where each participant was reading via videotaping. This location information, although rough, was especially useful when we related changes in NIRS measurements to participants' reading behaviors, because the videotaped location data was synchronized with the NIRS measurement data.

During the study, the following tasks were presented to each participant: (a) normal reading in English (60 seconds), (b) scanning in English (240 seconds), (c) finding topic sentences in English (240 seconds), (d) normal reading in Japanese (60 seconds), (e) scanning in Japanese (240 seconds), and (f) finding topic sentences in Japanese (240 seconds). A 60-second rest period was taken before and after each task. Thus, each session had six test blocks (tasks) between seven baseline blocks (resting time). During the breaks, the participant was instructed to relax and silently read a piece of paper on which letters were printed from the Latin alphabet or Japanese kana syllables (before the English and Japanese tasks, respectively). This was intended to clear the participant's WM activity before the next task. The order of task presentation was counterbalanced across participants so that ordering effects of task presentation could be nullified.

After each participant finished all of the tasks described above, a stimulated-recall interview was conducted to complement the NIRS data. Stimulated recall is a method used to collect learners' insights by presenting them with a stimulus, such as an audio or video recording, and asking them to recall the thoughts they had while performing a specific task (Gass & Mackey, 2000). In this study, the participant was shown both the passages and a video clip of him or herself working on each passage and was asked to report what he or she was actually thinking during the task. The NIRS data (i.e., graphical representations of the changes in blood hemoglobin concentrations) were also available for reference during the stimulated-recall interview. The session was recorded with an IC recorder. The entire experiment took approximately 60–70 minutes for each participant, including instructions and interviews.

NIRS Measurements

NIRS, the technique used in this study to measure the change in WM activation, is also known as "optical topography." It is a real-time, noninvasive brain-imaging technique that employs little participant restraint. The technique is especially suitable for research on recognition, language processing, and thinking processes because it can be conducted noninvasively and in real time. Many studies in the fields of brain science and psychology have indicated that NIRS is a satisfactory method of measuring brain activity (e.g., Ehlis, Herrmann, Wager, & Fallgatter, 2005; Horowitz & Gore, 2004; Kawaguchi, Ichikawa, Fujikawa, Yamashita, & Kawasaki, 2001; Kennan et al., 2002; Tsujimoto, Yamamoto, Kawaguchi, Koizumi, & Sawaguchi, 2004; among

others).

The NIRS technique uses near-infrared light to estimate changes in cerebral blood volume and oxygen saturation, both of which are good indicators of brain activity (Kawaguchi et al., 2001). Near-infrared light is absorbed by oxygenated hemoglobin (oxy-Hb) and deoxygenated hemoglobin (deoxy-Hb); however, not as much of this type of light is absorbed by other body tissues. Near-infrared light projected above the scalp from light emitters (semiconductor lasers) penetrates into the brain. The light is then absorbed and reflected onto optical probes attached to the surface of the scalp, which detect the near-infrared light reflected by their neighboring emitters. Because oxy-Hb and deoxy-Hb have different absorption spectra, changes in the concentrations of these molecules can be calculated according to the intensity of emitted infrared light at different characteristic wavelengths.

For NIRS measurements, this study used the ETG-4000 Optical Topography System (Hitachi Medical Co., Japan), which has a 52-channel array of optodes. Measurement probes with an inter-optode distance of 30 mm were inserted into sockets in a holder, which in turn was attached to the participant's head using a silicon helmet secured by adjustable straps. The recording channels resided in the optical paths in the brain, which were between the nearest pairs of emitter and detector probes. We used a 3×11 probe configuration involving 17 light emitters and 16 detector probes; this resulted in a total of 52 channels, which were arranged as shown in Figure 2. As shown by the figure, the receptive field for NIRS measurements covers most areas of the PFC, which is purported to be the locus of WM; the technique measures the hemoglobin concentrations in these areas (Figure 2).⁷ These 52 channels also contain the areas corresponding to the DLPFC and the VLPFC, on which previous studies of WM have focused (e.g., Lee, Folley, Gore, & Park, 2008; Tsujimoto et al., 2004). Especially, Tsujimoto et al. (2004) have demonstrated using the same NIRS technology that the PFC was activated when their subjects performed WM tasks. Their study thus confirms the applicability of NIRS to the measurement of WM in the PFC in the current study.

Because language and speech are known to be lateralized to the left hemisphere in right-handed individuals (e.g., Peng, 2005), we compared the data observed in the left hemisphere with those obtained from the right. The results of this comparison indicated that the right- and left-hemisphere data showed similarities, confirming the legitimacy of using all of the 52 channels covering both hemispheres of the brain in further analyses.

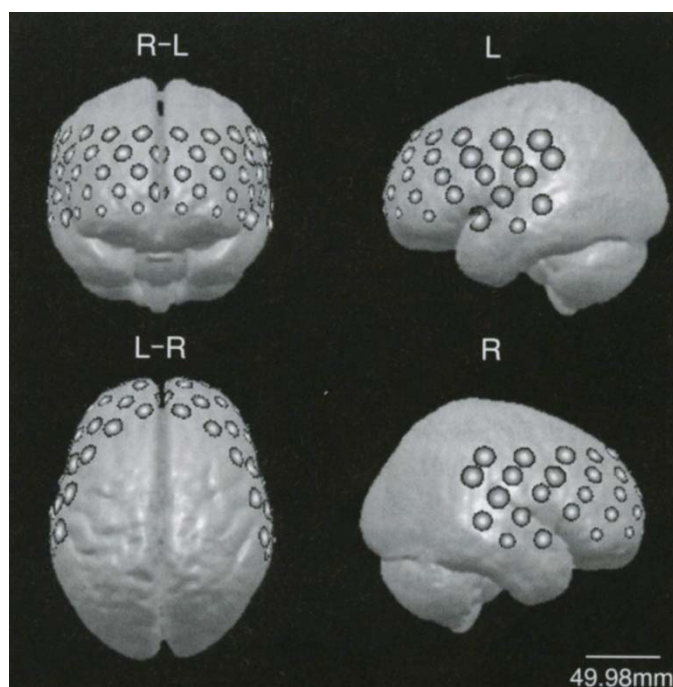


Figure 2. The approximate locations of areas covered and measured with 52-channel NIRS in the current study. Adapted from Fukuda, M., & Mikuni, M. (2007). Kinsekigaisen spectroscopy NIRS ni yoru Tougo Shicchoushou to Kanjoshogai no hojyoshindan [Near-infrared spectroscopy as a clinical laboratory test for diagnosis and treatment of schizophrenia and mood disorders]. *Seishin Igaku [Psychiatry]*, 49, 241. © 2007 by Igaku-Shoin. Reprinted with permission.

Data Analysis

Since several studies using NIRS have reported that the concentration of oxy-Hb is a clearer and more reliable indication of brain activity than that of deoxy-Hb (e.g., Tsujii, Yamamoto, Ohira, Saito, & Watanabe, 2007), we analyzed the relative changes in oxy-Hb during the six tasks.

The resting periods between tasks cannot completely restore the hemoglobin concentration to baseline (i.e., non-stimulated) levels because the tasks before or after them inevitably affect brain activity. The data may contain signals that are not directly related to the functional changes in hemoglobin concentration caused by the targeted cognitive tasks; thus, the measurements need to be corrected for measurement of brain function (Ehlis et al., 2005). We used a correction method called *integral analysis*, which applies a linear fitting function for baseline correction and employs resting periods as pre-task and post-task baselines (Figure 3). This correction method allowed us to quantify the relative changes in hemoglobin concentrations precisely.

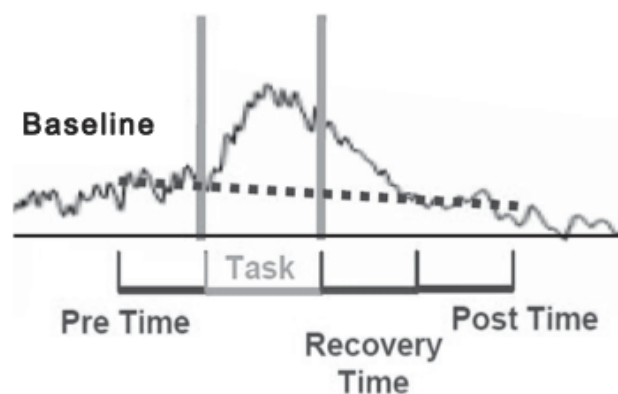


Figure 3. An example of how a linear fitting curve is applied and the baseline determined.

We then calculated the average concentration of oxy-Hb for each participant during each task. For the task of finding the topic sentences and writing a summary in either the L1 or L2, we excluded the data acquired while the participants were writing summaries from analysis because the study was only concerned with the former part of the task.

To address the research questions of the current study, we applied two-way repeated-measures ANOVAs to oxy-Hb levels as a dependent variable, with language (L1 and L2) and task (normal reading, scanning, and finding the topic sentences) serving as within-subjects factors. Prior to the analyses, the assumption of homogeneity of variance was checked with Mauchly's sphericity test, which substantiated the assumption. The threshold for statistical significance was set at the .05 level for all analyses. We also ran post hoc multiple comparisons with a False Discovery Rate (FDR; Benjamini & Hochberg, 1995) to control Type-1 errors (i.e., falsely reporting a statistical difference when none actually exists). Since the sample size was small in this study ($N = 12$), the Type-2 error rate (i.e., not detecting a statistical difference when there is one) may have been substantially inflated and the statistical power diminished. Therefore, we primarily interpreted the results of multiple comparisons in terms of effect sizes (Cohen's d) in addition to p values.⁸

The qualitative data obtained from the stimulated-recall interviews were used to corroborate the findings of the quantitative analyses. The transcripts of the interviews were subject to fragmentation and grouping according to the questions or issues arising from the NIRS findings by one of the authors. The fragmentation and grouping were then checked by the other authors.

Results and Discussion

The descriptive statistics summarizing the changes in oxy-Hb concentrations in each condition are presented in Table 2; the standard deviations are very high compared to the means. A

possible reason for this pattern of results may be individual differences in WM capacity (Morishita & Osaka, 2008); variability is known to be slightly greater in physiological data, such as those concerning brain activity.

Table 2. *Descriptive Statistics of the Oxy-Hb Concentration During Tasks*

Language	Task	Mean	SD
L2 (English)	Scanning	0.084	0.075
	Finding Topic Sentences	0.021	0.083
	Normal Reading	0.026	0.033
	Scanning	0.197	0.139
	Finding Topic Sentences	0.154	0.075

Note. $N = 12$; the unit of measurement is millimolar \times millimeter (mM \times mm).

The results of a 2 (languages) \times 3 (tasks) repeated-measures ANOVA with oxy-Hb levels as the dependent variable (summarized in Table 3) revealed a significant main effect of language, $F(1, 11) = 46.59$, $p = .001$, partial $\eta^2 = .63$; and task, $F(2, 22) = 8.37$, $p < .001$, partial $\eta^2 = .69$. There was no significant interaction between language and task: $F(2, 22) = 2.31$, $p = .12$, partial $\eta^2 = .17$.

Table 3. *Summary of the Results of the Repeated-Measures ANOVA*

Source	SS	df	MS	F	p	partial η^2
Language	0.17	1	0.17	18.61	.001	.63
Error (language)	0.10	11	0.01			
Task	0.23	2	0.11	23.99	<.001	.69
Error (task)	0.10	22	0.01			
language \times task	0.03	2	0.01	2.31	.120	.17
Error (language \times task)	0.12	22	0.01			

As for Research Question 1 (“Is the purported location of strategies (i.e., activation of WM during the strategy deployment) empirically supportable?”), the existence of a main effect of task and the absence of any interaction effects provide empirical support for Macaro’s (2006) hypothesis. That is, brain areas mainly corresponding to WM were activated when the participants consciously employed reading strategies, irrespective of language (i.e., for both the L1 and L2). These interpretations were further confirmed via post hoc multiple comparisons, which are summarized in Figure 4. Compared with normal reading, large effects ($d > .80$) in terms of oxy-Hb levels were observed in all of the strategy tasks in the participants’ L1 and L2 except for the topic-sentence task in their L1 (Japanese).

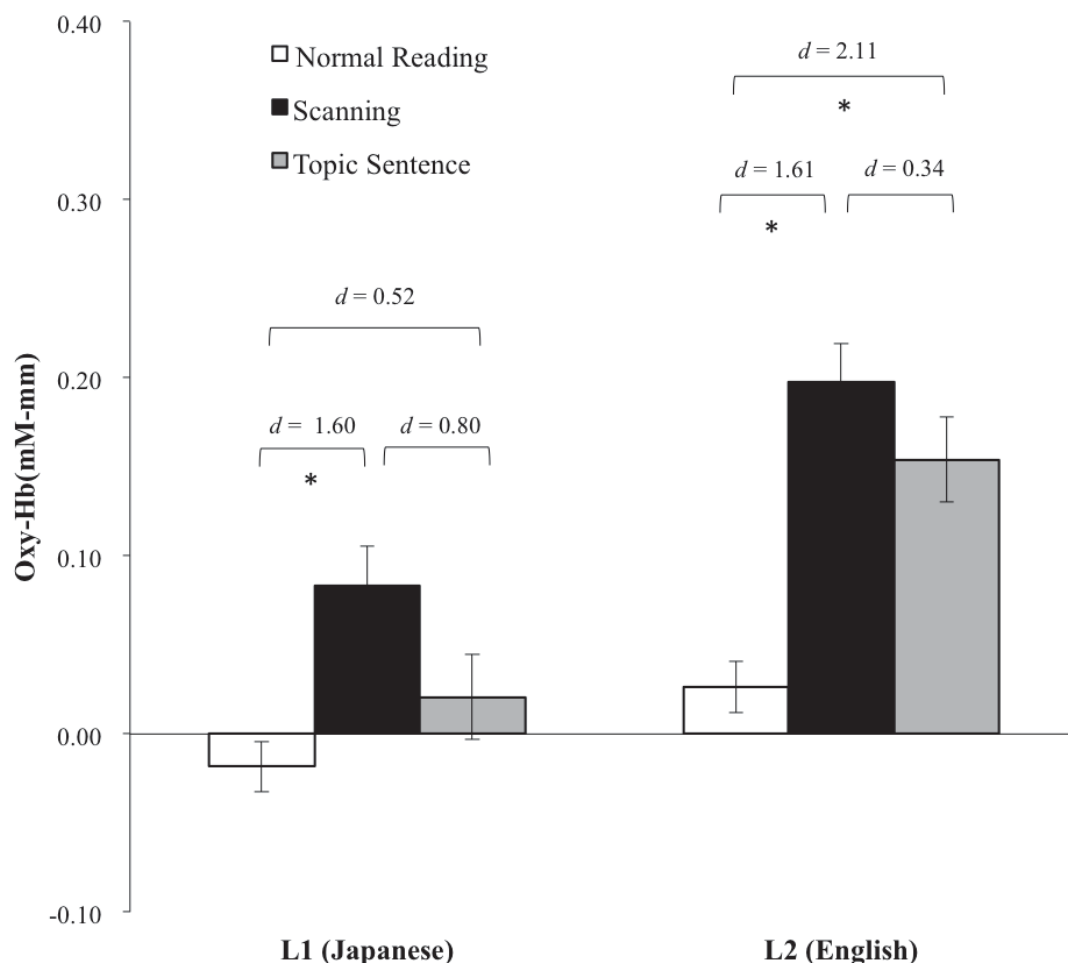


Figure 4. Concentration of oxy-Hb during each task and the results of multiple comparisons. Error bars indicate standard errors. The criteria employed for the effect size (d) (Cohen, 1988) were: $d = .20$ (small effect), $d = .50$ (medium effect), and $d = .80$ (large effect). * $p < .05$ (significant with FDR). mM-mm on the Y-axis stands for millimolar millimeter.

The qualitative data from the stimulated-recall interviews also supported these findings, showing that the participants consciously deployed strategies when they were engaged in both scanning and finding topic sentences in their L1 (Japanese) and L2 (English). On the other hand, when the participants were engaged in normal reading, they did not deploy reading strategies. The following excerpts (Excerpts 1, 2, and 3), which are drawn from the stimulated-recall data, reflect the different levels of conscious cognitive processing between the normal reading task and the two strategic reading tasks (the originals were in the L1; the translations are ours):

Excerpt 1

[Explaining how she dealt with normal reading in her L1 and L2]

I had no difficulty reading through the paragraphs. I just read through and understood most of what the passage meant to convey.

Excerpt 2

[Reflecting the deployment of strategies for the finding-the-topic-sentences task in both the L1 and L2]

I especially paid attention to the paragraph structure and predicted what would appear next to the topic sentences.

Excerpt 3

[Describing how he used strategies for the *scanning* task in his L2]

I tried to search for the keywords given in the questions. I knew I only had to refer to the paragraph in which the information was given.

As Excerpt 1 shows, to understand the passage in the normal-reading task does not require much effort; therefore, it causes little change in WM activation in the target brain areas. This is because the participants did not strategically read the passage in order to achieve an objective; even when they did, they used strategies that have reached the level of “automaticity” (Macaro, 2006, p. 329). The neuroimaging results of this study suggest that once the reading strategies are employed consciously (i.e., they are brought back under attentional control), WM is activated.

The overall findings regarding Research Question 1 were the following: the brain areas corresponding to WM were activated when the participants consciously employed cognitive strategies while reading, irrespective of language (in both the L1 and L2). These findings provide much-needed empirical support for the framework of Macaro (2006, 2007), thereby consolidating the foundations of learner-strategy research.

The main effect of language was examined in order to answer Research Question 2 (“Is the activation of WM in L1 strategy deployment significantly lower than that in L2 strategy deployment, as expected on the basis of Macaro’s (2006) framework?”). The results indicate a significant main effect of language with no significant interaction effect. Thus, we concluded that the activation of WM in L2 strategy deployment is much higher than WM activation in L1 strategy deployment. These brain-activation patterns during the tasks suggest that the learners needed to recruit lower oxy-Hb concentrations in L1 reading tasks than in L2 reading tasks.

The presence of less activation of WM during the use of L1 reading strategies implies that employing strategies is easier in the L1 than in the L2 for the participants, perhaps because the lower cognitive load involved in L1 processing leaves a larger amount of space available in WM. However, this ease of employing strategies cannot be readily transferred to L2 reading, in which the cognitive processing load is heavier than that in the L1. Thus, L2 linguistic processing consumes much more space in WM even among the advanced L2 learners who participated in the current study. This supports the findings of Nambiar (2009), who examined the cross-linguistic transferability of reading strategies among bilingual people.

The following excerpts drawn from the stimulated-recall interviews more clearly highlight the participants’ familiarity with and expertise in L1 strategy deployment:

Excerpt 4

[Explaining how he used the strategies in the L1 scanning task]

To find the answer to a question, I first checked the key words in a question and then scanned the passage for those key words. When I found them in a sentence, I read that sentence and the sentences before and after it. I usually did not read the other sentences.

Excerpt 5

[Reflecting the deployment of strategies in the finding-the-topic-sentences task in the L1]
I am familiar with this way of reading [i.e., finding the topic sentences to understand the main idea of the passage] in Japanese [L1]. Since I usually use it in reading Japanese, using it in this experiment [L1] was not difficult at all for me.

These excerpts illustrate that familiarity and expertise with strategic reading in the L1 might result in lower activation of WM. At the same time, the higher activation of WM observed in the L2 tasks could imply that the L1–L2 difference is great: Even advanced L2 learners need to exercise more conscious control over strategy deployment in the L2. The following excerpt from the stimulated-recall interviews illustrates this difference:

Excerpt 6

[Reflecting the deployment of strategies in the finding-the-topic-sentences task in the L1 and L2]
When I read the passage in L1, I drew its outline in my mind, but I wasn't able to do so when I read the L2 passage. When I read in L2, I had to concentrate on understanding English, and there was no room in my mind to do anything else, such as creating the outline of the passage.

Other participants hinted at possible reasons why reading in the L1 resulted in lower WM activation (Excerpts 7 and 8).

Excerpt 7

[Explaining how he used the strategies in both the L1 and L2 tasks]
Overall, it was easier for me to use the strategies of both scanning and finding the topic sentences in L1 tasks than in L2 tasks. I think this was the case because I am more familiar with reading in L1 than in L2. Also, I know fewer words in L2 reading than in L1. So, I must use my brain harder to understand each sentence in L2 reading than in L1 reading.

Excerpt 8

[Explaining how he used the strategies in the L1 and L2 scanning tasks]
Comparing the L1 and L2 reading, it is easier for me to scan the passage in L1. This is because you can easily scan the Chinese characters [ideograms] in L1 [Japanese]. On the other hand, you have to concentrate on finding a certain word made up of alphabetical letters [phonograms] in L2 [English] scanning.

Conclusion

The present study does have several limitations. The first concerns the possible effect of differences between passages. Although the nature of the tasks was similar between passages and the topical familiarity and text difficulty of the passages were controlled, each reading passage used in the present study was inherently different (i.e., they were not the same in terms of topic

and difficulty). The differences between passages might have affected the results reported above. Replication studies designed similarly to this one are therefore urgently needed so that this line of criticism can be neutralized.

A second limitation is that this study only investigated the use of cognitive strategies. Since recent strategy literature has placed increasing importance on metacognition, it might be desirable to investigate the use of metacognitive strategies (in combination with cognitive strategies) in future research. Particularly, it would be interesting to examine the effects of metacognitive strategy use on cerebral activation.

A third limitation is the possibility that the learners could use other cognitive strategies than the designated one in each task. Although the participants confirmed that they had used the designated strategy for each task (or did not use any particular strategy in normal reading) during the stimulated-recall interview sessions, it might be possible that this confirmation did not necessarily reflect reality. Therefore, future studies need to introduce better methods to verify the use of the designated strategy (or the non-use of other strategies) in each task.

A fourth limitation of this study is that the anatomical localization of WM is unknown. In this study, we took a “localist” approach to brain functioning in which we assume that certain parts of the brain work to execute WM. This approach reflects a broad consensus within the field of brain-imaging research about the approximate location of WM (e.g., Beardsley, 1997; Fuster, 2008; Osaka, Logie, & D’Esposito, 2007). However, as the debate concerning the localization of WM has not yet reached a definitive conclusion (e.g., Zurowski et al., 2002), future studies will need to reflect the result of the debate concerning this issue.

Keeping these limitations in mind, our findings and their implications can be summarized as follows: the results of the present study confirmed elevated WM activation in the deployment of the L1 and L2 strategies above that were observed during a control reading task. This finding attests to the validity of an important part of Macaro’s (2006) theoretical framework, (i.e., the localization of cognitive strategy use) and provides much-needed empirical support for the field of strategy research.

The present results also show that WM activation is lower in L1 reading tasks than those in the L2, as postulated by Macaro (2006). This finding can be explained in terms of the interplay between the cognitive load of language processing and the capacity of WM: Lower activation of WM in the L1 implies that it is easier for the participants to employ strategies in the L1, perhaps because the lower cognitive load involved in L1 processing leaves a larger amount of free space available in WM. However, this ease cannot be readily transferred to L2 reading, wherein the cognitive load is heavier than that of reading in the L1; thus, linguistic processing in the L2 consumes much more space in WM than that in the L1. This line of interpretation perfectly matches the predictions of Macaro’s framework.

The findings reported above thus confirm a very basic layer of Macaro’s (2006) theoretical framework and serve to establish the cerebral basis of strategy use, thereby reinforcing the theoretical underpinnings of language-learner strategy research.

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Notes

1. See Gao (2007) for responses to the issues raised by Dörnyei and his colleagues (Dörnyei, 2005; Tseng, Dörnyei, & Schmitt, 2006).
2. In a similar vein, Ikeda and Takeuchi (2000), along with Hsiao and Oxford (2002), suggested the importance of conducting task-based strategy research to examine learners' dynamic use of strategy in specific task settings.
3. WM is used for "temporary storage and manipulation of information that is assumed to be necessary for a wide range of complex cognitive activities" (Baddeley, 2003, p. 189). For this reason, WM is regarded as facilitating cognitive processes, a construct that has been established through a number of experiments (Baddeley, 1997).
4. Baddeley (2000) added a third subsidiary system, the episodic buffer, which functions as a temporal information-storage bank and is able to bind information from the other two subsidiary systems. The anatomical location of the episode buffer is presumed to be in the frontal areas (p. 421).
5. TOEIC stands for the Test of English for International Communication (TOEIC). TOEIC scores range from 10 to 990. As of 2007, the average TOEIC score for Japanese test-takers was 579, and that for university students was 431 (TOEIC Steering Committee, 2008). According to the Educational Testing Service (2006), "TOEIC has been used to measure the English proficiency of non-native English-speaking people."
6. Although the participants read different sets of passages, they showed similar patterns of reactions to the difficulty of the passages, which were assessed on a 5-point Likert-type self-report scale. This indicated that the differences among the passages did not influence the results through variability in difficulty levels.
7. Several models of WM have been proposed (for review, see Miyake & Shah, 1999), but since this study validates Macaro's (2006) theoretical framework of strategies for language learning

and use, we adopted Baddeley's (1987, 1997) model of WM in this study, on which Macaro's model is based, in this study.

8. Effect sizes indicate the magnitudes of the effects or the strength of the relationships (American Psychological Association, 2001). For a comprehensive explanation of effect sizes, see Cohen (1988) and Kline (2004).

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