The Effects of Onset-Age and Exposure Duration on the L2 as Observed in Brain Activation: an fNIRS Study

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Abstract

This study aims to examine how the age of exposure to L2 English (onset-age or OA) and exposure duration (length of residence or LOR) affect brain activation using the fNIRS machine. Thirty-two Japanese-English bilinguals were divided into four groups according to the level of English proficiency based on their OA and LOR. While wearing the brain cap to monitor brain waves, the participants were individually presented with two tasks - a verbal fluency task and a numeral task in two languages, English and Japanese. Behavioural data showed no significant differences among four groups, which proved the task difficulty was equal among the groups. The results firstly demonstrated that the earlier one's initial intensive and extensive exposure to an L2 is, the less the brain activation in both hemispheres is observed, even in those who were exposed to their L2 before the critical period. The second finding revealed that brain activation decreases in both hemispheres as one's L2 proficiency improves.

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1. Introduction

1.1 Lateralization

The specialization of various functions into the two cerebral hemispheres is called lateralization, seen for example in language processing which is predominantly carried out in the left hemisphere in over 90% of right-handed people (*e.g.,* Knecht, 2000). This is only a tendency, however, as the right hemisphere does become involved in certain aspects of language use such as prosody. The regions of the brain used for language include Broca's area for language production, which is located in the inferior third frontal gyrus in the dominant cerebral hemisphere (Brodmann areas 44 and 45). Another brain region is Wernicke's area supporting language comprehension and it is found in the posterior section of the superior temporal gyrus in the dominant cerebral hemisphere (Brodmann area 22).

The age at which language lateralization takes place is controversial to date. Recent development of neuroimaging technologies allows us to investigate brain activation in small children in a non-invasive way. Wartenburger *et al.* (2007), for instance, found that by using fNIRS (functional near-infrared imaging), four-year-old children already showed signs ofL1 lateralization in the left hemisphere. Other researchers report on lateralization beginning at an even earlier age. In Dahaene-Lambertz's (2000) study, 4-month-old infants showed left hemisphere involvement when presented with auditory stimuli and in Peña *et al*'s (2003) research, infants as young as two to five days old displayed more activation in the left hemisphere while listening to children's stories. These findings suggest that L1 lateralization in the left hemisphere seems to occur quite early on.

Some researchers have explored whether the brain processes L1 or L2 differently. Perani *et al.* (1997) found that there are no cortical response differences observed between early bilinguals (onset age of bilingualism, zero to four years of age) and late bilinguals (onset age of ten years of age or older) when listening to stories. Quaresima *et al.* (2002) discovered that early bilinguals (onset age of zero to five years of age) showed similar activation patterns in the left lateral frontal lobe whether a translation task was from L1 (Dutch) to L2 (English) or *vice versa.* Weber-Fox and Neville (1996) argued that for early and late bilinguals there were no differences in brain activation during a *semantic* judgment task, but there were differences in the activated regions on an L1 and L2 *grammatical* judgment task. This issue of task-dependency is also reported by Yokoyama *et al.* (2010) who researched late Japanese-English bilinguals and found that different brain regions are used to process more complex structures (passive form) while the same brain areas are activated on easier tasks in both Japanese and English. In contrast, Suh *et al.* (2007) who examined Korean-English bilinguals found that they used a totally different cerebral network for their L1 compared to their L2, in comprehending syntactically complex sentences. Thus, the research into which areas of the brain are activated for L1 or L2 is still inconclusive.

1.2 The Critical Period and L2 proficiency

The critical period hypothesis for language acquisition was first proposed by Lenneberg (1967 and 1975) who argued that it is difficult to achieve native-like proficiency once one passes the critical period (puberty). Data supportive of this hypothesis have been presented by some researchers such as Johnson & Newport (1989). They examined immigrants to the U.S.A. whose age of arrival varied from 3 to 39 years old, using a grammatical judgment test. They found that age 16 marked the dividing line: those who arrived before 16 were able to produce more accurate L2 in comparison to those whose arrival was after that age. Luk and Shirai's (2009) research produced similar results, though the dividing age was found to be a lot earlier age than 16. On the other hand, Hakuta *et al.* (2003) rejected the critical period for L2 acquisition.

There are some researchers who attempted to identify whether L1 and L2 processing takes place in the same or different brain regions, depending upon one's onset age for L2. Kim *et al*, (1997) found early bilinguals (onset age in infancy) show that both the L1 and L2 activate the same region in Broca’s area whereas late bilinguals (OA in early adulthood) showed activation in a different region of Broca’s area. Dehaene *et al.*, (1997) reported their bilingual participants (onset age before seven) as showing a left-hemispheric dominance for comprehending L1, but during the L2 listening task, the right hemisphere showed signs of activation. Sakai (2005) argues cortical activation is influenced not only by the L2 age of acquisition, but also by the proficiency level. Oishi (2006) found that Japanese EFL learners showed a positive correlation between their proficiency and the level of cerebral activation until they had reached a certain level of proficiency with TOEFL and TOEIC tests **-** little activation in novice learners, followed by hyper-activation in advanced learners and reduced activation in very proficient learners.

Thus, the onset age of L2 acquisition and proficiency level appear to be key variables when examining if language processing occurs in the same cerebral region for the production of the L1 or L2.

1.3 Research Questions

Research Question 1: Do simultaneous bilinguals (OA at birth) show different brain activation in their L2 use when compared to sequential bilinguals (OA before the age of seven)?

Research Question 2: Is the length of exposure to L2 important in brain activation when the L2 is learned after the critical period?

2. Methodology

2.1 Participants

A total of 32 subjects (14 male and 18 female; *M*=17.41, *SD*=7.75, age range of 8.03 to 45.09) participated in this study. All of them were right-handed as assessed with the Edinburgh Inventory (Oldfield, 1971). The participants were divided into four groups. Group 1 (G1, hereafter) consisted of eight subjects (six male and two female) whose English exposure began at birth and who continued to be exposed to both Japanese and English languages up until this experiment took place. Group 2 (G2) consisted of nine subjects (three male and six female) who were first exposed to English before the age of seven years old and thus prior to the critical period for language acquisition. They had a mean length of residence in English-speaking countries of 8.78 years. Group 3 (G3) consisted of seven subjects (three male and four female) who were exposed to English intensively for varying periods of from one to six years after the age of 16. Group 4 (G4) consisted of eight subjects (six male and two female) who were in seventh grade at a public junior high school. Thus, G1 participants are labeled as simultaneous bilinguals. G2 became bilingual sequentially. G3 learned English as a foreign language both in Japan and in English speaking countries. In contrast, G4 had just begun to learn English in a formal classroom setting in Japan six months prior to this experiment. The participants' demographic data are summarized in Table 1.

Table 1. Participants' demographic data

		Onset age (OA)			Length of residence (LOR)		
Group	*N*	*M*	*SD*	*range*	*M*	*SD*	*range*
1	8	0.00	0.00	0.00	10.94	2.30	8.03-15.08
2	9	4.78	2.11	0.00-7.00	8.78	4.35	5.00-16.00
3	7	20.57	4.86	16.00-30.00	2.57	2.07	1.00-6.00
4	8	12.00	0.00	0.00	0.60	0.00	0.60

Participants self-evaluated their own language level in the four skills (speaking, listening, reading, and writing) in Japanese and English on a five-point Likert scale with '5' being superior, '3' equal, and '1' inferior to native speakers of the same age (Table 2).

Table 2. Self-evaluation of four skills in Japanese and English

	Japanese				English			
	Reading	Writing	Listening	Speaking	Reading	Writing	Listening	Speaking
G1	2.38	2.25	2.63	2.63	2.88	2.88	2.63	2.88
G2	2.67	2.33	3.00	2.78	2.44	2.56	3.11	2.56
G3	3.57*	3.29	3.71*	3.14	2.29	2.00	2.43	1.86
G4	2.83	2.83	2.83	2.83	1.17*	1.17*	1.17*	1.17*

$^*p<.05$

Levene's test for homogeneity of variances was checked and it was found that we did not violate the homogeneity of variance assumption. T-tests revealed some statistically major features among the groups: (1) G3 rated their Japanese proficiency in two skills (reading and listening) better than G1, and (2) G4 self-evaluated themselves statistically inferior to G1 in all four skills of English. This reveals that G3, with their overseas experiences, may have a greater linguistic confidence and that G4, with only six months of English learning, find themselves equipped with very limited skills in English.

Prior to the experiment, a signed consent form was obtained from all the participants or from their parents, if they were under 18 years of age. This study was approved by the Ritsumeikan University Institutional Ethics Committee in Japan.

2.2 Procedure

Participants were individually shown into a laboratory and seated in a chair with their eyes approximately 30 cm away from the monitor (Panasonic Let's Note CF-F9). While a flexible cap with 27 fiber probes was being placed on their head, information was gathered on their language background, right or left-handedness, and self-assessment of their four skills (speaking, listening, writing, and reading) in the two languages - Japanese and English. Once the cap was appropriately placed and connected, photos were taken to record the position of the cap from three angles—from the left, right and front. Then, a video clip was shown to inform the participants of what the experiment involved. When participants were made fully aware of the task, they were told that it was their right to stop it at any time if they felt uncomfortable, once the experiment had started. Upon completion of the experiment, each participant was given an appropriate token of gratitude—a book voucher.

2.3 Tasks

Using TOEFL or TOEIC items as tasks in brain research has been harshly criticized as the tasks involve too many intervening variables to differentiate (Ishikawa, 2009; Taura *et al.*, 2010). Verbal fluency tasks are frequently used to elicit brain activation data from bilingual subjects because of the relative ease to make comparable tasks between two languages (e.g., Arai *et al*., 2006; Ehlis *et al.*, 2007; Fallgatter *et al.*, 2004; Kameyama *et al.*, 2004; Schecklmann *et al*. 2008; Taura *et al.*, 2010).

Bilingual children are reported to possess better metalinguistic awareness (Bialystok, 2012) and be more capable of handling cognitively demanding tasks such as the bilingual Stroop test (Taura, 2008). More cognitively demanding tasks trigger greater brain activation in the pre-frontal lobe as disclosed by a brain-imaging study by Izzetoglu *et al.* (2004). Stephan *et al.* (2003), using cognitively demanding tasks, have also found that letter decision tasks induce activation in the left anterior cingulate cortex and left inferior frontal gyrus whereas visuo-spatial decision tasks activate right anterior cingulate cortex and right parietal areas. Thus, employing a mathematical task, where participants need to attend to both letter and colour information (further explained below), is expected to activate both hemispheres more since the task is cognitively more demanding than a simple verbal task.

Thus, two types of tasks were devised for this study. The first task was a simple verbal fluency task while the second verbal task was cognitively more demanding as the participants needed to control their answers depending on the colour and nature of the one-digit numbers presented on the PC screen.

2.3.1 Verbal Fluency Task

The Verbal Fluency Task (VFT) included four sub-tasks as shown in the blocked design in Figure 1 that also shows the task stimuli and the timing of the tasks. The experiment began with a 30-second rest. Then the first letter task was given for 30 seconds followed by a 60-second rest, before the second letter task began. This pattern repeated itself again with category tasks in each language. At the end of the fourth task, there was another rest lasting for 30 seconds. To offset the language sequence effects, a counter-balanced version was used for every second participant.

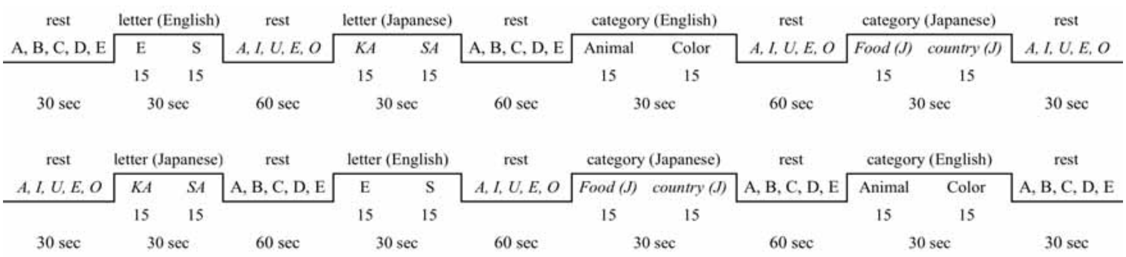


Figure 1. Blocked design for Verbal Fluency Task

Two kinds of tasks were given to the participants: the letter task and the category task in Japanese and English. For the Japanese letter task, *hiragana* prompts were projected onto the computer screen of the letters 'ka' or 'sa', and the participants were then expected to say aloud as many Japanese words as possible that started with 'ka' in the first 15 seconds and 'sa' in the second 15 seconds. The English letter task used the letters 'E' and 'S' in the same way. Meanwhile, in the Japanese category task, participants were required to produce as many words as they could that related to cue words such as 'country', where for example they may have said 'Japan' or 'France'. Both Japanese and English category tasks had two category words that were shown on the PC screen for 15 seconds each. The actual category words shown in English were 'animal' and 'colour' while the words 'food' and 'country' were projected onto the screen in Japanese. Our decision to use such English letters and categories are based on previous studies by Schecklmann *et al*. (2008) and Ehlis *et al*. (2007) while the *hiragana* examples were selected from Japanese studies (e.g., Arai *et al*., 2006; Kameyama *et al*., 2004; Murai *et al*., 2004).

2.3.2 Numeral Task

There were three kinds of sub-tasks that made up *The Numeral Task*—the bilingual task, the English task, and the Japanese task (Figure 2).

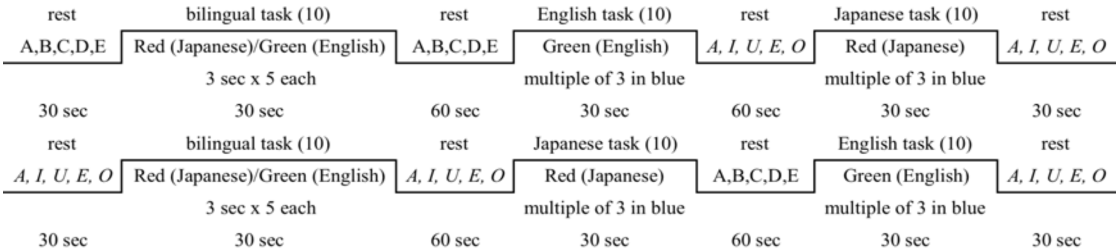


Figure 2. Numeral Task

In each task, ten different slides were presented for three seconds each. *The Numeral Task* was comprised of each task (30 seconds in length) followed by a 60-second rest, except for the first and last rests, which were 30 seconds long. The ten slides each presenting a one-digit number, were shown on the PC monitor one by one (Figure 3). Each stimulus was shown for 3 seconds. The bilingual task involved both English and Japanese, with a number projected on each slide in either red or green. A number in red required the participants to say it aloud in Japanese while a green number had to be identified aloud in English. For the English task using only the English language, a number was shown on the slide in either green or blue. A green number had to be named aloud in English but when it was in blue, only the number 3 or a multiple of 3, was to be said aloud. For example, when the slide '3' in blue was shown, the correct answer was 'three' in English but when a slide with a blue '7' was presented, they had to remain silent as 7 is not a multiple of 3. The Japanese proceeded likewise, with the only difference being the red color of the Japanese numbers instead of green. The sequence of the three tasks was counter-balanced for every second participant.

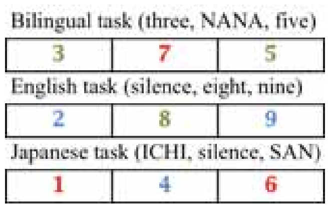


Figure 3. Examples of the Numeral Task and answers

2.4 Brain Imaging Technique

Among the variety of brain imaging techniques, the non-invasive functional neuro-imaging method known as fNIRS is said to be easier to use and sensitive to detecting small substance concentrations, with a high temporal resolution (Toga and Mazziotta, 2002). In principle, fNIRS measures brain activation using changes in the intensity of light detected by source and detector probes that are attached to the head with a harmless light that penetrates the brain. Other brain imaging techniques including fMRI (functional magnetic resonance imaging), PET (positron emission tomography), and MEG (magnetoencephalography) require large and bulky instruments which make it difficult for small children to be examined. In comparison, fNIRS uses light via fibre optics, which can even allow babies to be examined (Miyai *et al.*, 2001). In addition, fNIRS is sensitive to a very low substance concentration using a fluorescence method and the result is similar to a PET scan without the disadvantage of radioactive tracers. Temporal and spatial resolution differ vastly from one brain imaging method to another: high temporal resolution is obtained using the MEG eletrophysiological method (starting from 1 m.s.) while hemodynamics-based techniques such as fMRI (starting from 1 mm) provide a greater spatial resolution. fNIRS offers a smaller, easier-to-use option to monitor vascular, metabolic-cellular, and neuronal responses with a high temporal resolution of about 1,000 m.s., despite a low spatial resolution of about 3 cm. It is also recognized that fNIRS data are consistent with fMIR data in predicting hemispheric dominance on linguistic tasks (e.g., Kennan *et al.*, 2002). fNIRS has been widely used and proved to be useful in various disciplines (see Kovelman *et al.*, 2008 for summary). Therefore, for this study where younger children were involved, we decided to use an fNIRS - a multichannel continuous wave optical imager (Shimadzu FOIRE-3000).

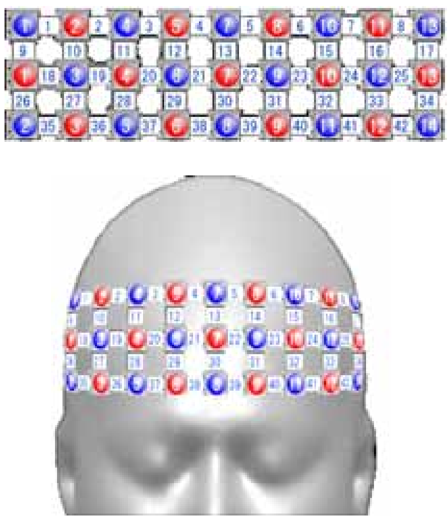


Figure 4. Flexible brain cap with probes placed on head

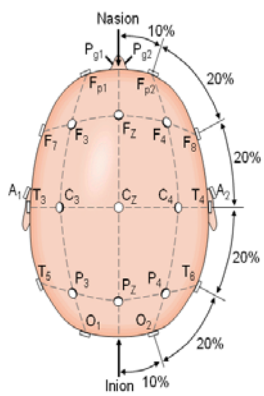


Figure 5. International 10/20 system

Shimadzu FOIRE-3000 has 13 emitters and 14 receivers, 3 centimetres apart from each other to detect 42 areas (channels). The fNIRS machine uses three wavelengths of near-infrared light (780±5nm, 805±5nm, 830±5nm). According to the International 10/20 system (Jasper, 1958), emitters and receivers of fNIRS were placed bilaterally over the frontal lobe, including Broca's area in the left inferior frontal cortex, with the lowest probes being positioned along the T3-Fp1-Fz-Fp2-T4 line (Figures 4 and 5). The length between the nasion (right above the nose) and the inion (the most prominent projection point of the occipital bone at the base of the skull) was measured to pinpoint the one-tenth distance from the nasion where the eighth receiver hole is aligned. Next, the distance between the midpoints of the two ears was measured to make sure that the one-tenth above each mid-ear point was aligned with the T3-Fp1-Fz-Fp2-T4 line. These two steps were taken for all the participants.

Our decision to examine the frontal lobe in both hemispheres was based on findings from Herrmann *et al.* (2003 and 2005), Just *et al.* (1996), Kameyama *et al.* (2004), and Yamadori (1998) that in a language task, not only the left laterosuperior temporal cortex (Wernicke's area) and the left inferior frontal gyrus (Broca's area) but also their homologous right-hemisphere areas are found to be activated, though the right areas had much smaller volumes of activation.

2.5 Data analysis

Data from the fNIRS were processed using the Shimadzu FOIRE (a functional optical imagery software for research) and PASW SPSS software. The first stage involved identifying in the individual participants, the two distinct areas of the brain for this study, namely, Broca's area and its homologous area in the right hemisphere of the prefrontal lobe. After checking that all the probes were aligned properly, we visually identified Broca's area and its right homologous area and wrote down their corresponding probe numbers. Diagrams displaying changes in oxygenated hemoglobin (oxy-Hb), deoxygenated hemoglobin (deoxy-Hb), and total hemoglobin (total-Hb) using the FOIRE software were produced, in order to discard any data at particular channels that showed the involvement of artefacts which may have been due to a jerking movement of the participant or probes popping out of the holder sockets. Despite its excellent temporal resolution, fNIRS lacks spatial resolution (Toga and Marital, 2002), therefore we needed to include several channels of data to cover the designated two regions of the brain. Broca's area generally included channels 25, 33, and 34 while its right hemispheric counterpart included channels 18, 26, and 27 in most participants.

FOIRE-3000 shows three different fNIRS parameters (oxy-Hb as a red line, deoxy-Hb as a blue line, and total-Hb as a green line on the monitor). Based on the findings that fNIRS oxy-Hb exhibits a high correlation with the blood oxygenation level dependent (BOLD) signal used in fMRI (e.g., Ryo *et al.,* 2008; Shimoyama *et al.,* 2006; Toronov *et al.,* 2007), and the data produced may therefore be used to represent all three parameters (Fukuda, 2009; Malonek *et al.*, 1997; Strangman *et al.,* 2002), this study focused solely on oxy-Hb.

fNIRS raw data (mM-mm) reflect the comparison between the change in concentration of hemoglobin and wavelengths of near-infrared light (fNIRS value) from 130 milliseconds before. Therefore, the raw data cannot be used for intra- and inter-subject analysis and need to be subtracted from the baseline data (e.g. Yokoyama, 2010; Peterson *et al.,* 1988). In other words, the raw fNIRS data during each task need to be subtracted from the fNIRS data in the preceding rest task. This subtraction method was originally devised by Peterson *et al.* (1988) using PET scanning and has since been widely used in neuroimaging studies. The subtraction process takes place in the following manner: (1) fNIRS (oxy-Hb) data in the channels (24, 25, 33, 41, and 42, for instance) that were identified as Broca's area are averaged out for a particular 30-sec task, (2) the same calculation is conducted for the preceding 30-sec rest time, and (3) the rest average fNIRS is subtracted from the task average fNIRS (Table 3). The same procedure is repeated with the fNIRS data in the right hemisphere. For a group comparison, these individual subtraction figures are averaged out within each group as representative figure.

Table 3. Subtraction of the average rest-time fNIRS data from the average task fNRIS data

first 30-second long rest							English letter fluency task							
time second	ch-24 oxyHb	ch-25 oxyHb	ch-33 oxyHb	ch-41 oxyHb	ch-42 oxyHb	5 channels average	time second	ch-24 oxyHb	ch-25 oxyHb	ch-33 oxyHb	ch-41 oxyHb	ch-42 oxyHb	5 channels average	**SUBTRACTED fNIRS**
0.000	0	0	0	0	0	0.000000000	30.135	0.0228	0.0304	0.0024	0.0203	0.0281	0.020819400	**0.020819400**
0.205	-0.001	0.00736	-0.0054	-0.0021	-0.0005	-0.000335400	30.340	0.0205	0.0286	0.0009	0.0148	0.0081	0.014564000	**0.014899400**
0.410	0.00194	-0.0046	-0.0111	-0.0076	0.00441	-0.003381000	30.545	0.0171	0.036	-0.008	0.0076	0.0048	0.011449600	**0.014830600**
0.615	-0.0037	0.00134	-0.019	-0.0161	-0.0129	-0.010079200	30.750	0.0241	0.0386	0.0242	0.0185	0.0335	0.027784600	**0.037863800**
0.820	-0.001	0.00144	-0.0118	-0.0019	-0.0159	-0.005822600	30.955	0.0118	0.0355	0.0078	0.0152	0.0311	0.020266200	**0.026088800**
1.025	-0.0023	-0.0052	-0.0134	-0.0065	-0.0127	-0.008018000	31.160	0.0206	0.0383	0.0162	0.0206	0.0154	0.022211200	**0.030229200**
1.230	0.0028	-0.0058	-0.0258	-0.0184	0.00057	-0.009303600	31.365	0.0218	0.0273	0.0103	0.0228	0.0436	0.025157600	**0.034461200**
1.435	0.00394	0.00372	-0.0092	-0.0094	-0.0103	-0.004235000	31.570	0.0252	0.0296	0.0095	0.0113	0.0164	0.018383200	**0.022618200**
1.640	0.00984	0.00292	-0.018	-0.0086	-0.0058	-0.003939600	31.775	0.0203	0.0202	0.0038	0.0174	0.0347	0.019270800	**0.023210400**
-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
-	-	-	-	-	-	-	-	-	-	-	-	-	-	**-**
28.085	0.01767	0.02137	-0.0033	0.01104	0.02103	0.013563600	58.220	0.0357	-9E-04	0.0637	0.0842	0.1547	0.067459200	**0.053895600**
28.290	0.02007	0.01693	0.00357	0.01087	0.02382	0.015052200	58.425	0.0474	-0.002	0.0621	0.0877	0.1417	0.067288600	**0.052236400**
28.495	0.01728	0.02333	-0.002	0.0134	0.03218	0.016836800	58.630	0.037	-0.002	0.0656	0.0853	0.1577	0.068688800	**0.051852000**
28.700	0.02184	0.02495	0.01194	0.01865	0.0384	0.023156800	58.835	0.0444	0.001	0.0603	0.0704	0.145	0.064225600	**0.041068800**
28.905	0.01679	0.02183	0.01111	0.02876	0.03296	0.022289600	59.040	0.0521	0.0263	0.0627	0.0793	0.1501	0.074104000	**0.051814400**
29.110	0.01507	0.01056	0.0057	0.01141	0.01425	0.011398400	59.245	0.0488	0.0324	0.0729	0.0886	0.1604	0.080623600	**0.069225200**
29.315	0.01837	0.02798	0.00222	0.01677	0.01975	0.017018400	59.450	0.0479	0.0326	0.0711	0.0894	0.1384	0.075891000	**0.058872600**
29.520	0.02377	0.03376	-0.0024	0.01607	0.02364	0.018973600	59.655	0.0449	0.0198	0.0569	0.0791	0.1277	0.065661200	**0.046687600**
29.725	0.02439	0.01803	0.00131	0.01951	0.01933	0.016516800	59.860	0.0532	0.0494	0.0722	0.0815	0.1415	0.079546200	**0.063029400**

3. Results

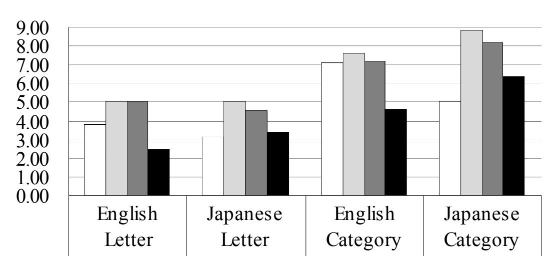
The results of the two experiments– the *Verbal Fluency Task* and *Numeral Task*–are provided here. Each task is dealt with separately showing oxy-H in mM-mm.

3.1 Verbal Fluency Task

3.1.1 VFT behavioural data

The average number of words produced in each task are as follows: 4.1 words in the

English letter task, 4.0 in the Japanese letter task, 6.6 in the English category task, and 7.0 in the Japanese category task (for individual group averages, see Figure 6). The chi-square test revealed that there was no significant difference among groups in the number of output words uttered in each of the four *VFT*: the English letter task (χ^2=33.492, *df*=33, *p*>.05), the Japanese letter task (χ^2=33.168, *df*=33, *p*>.05), the English category task (χ^2=49.782, *df*=45, *p*>.05), and the Japanese category task (χ^2=51.468, *df*=45, *p*>.05). There was no significant difference when four tasks were compared and all groups combined (χ^2=70.608, *df*=63, *p*>.05). These results showed that there were no differences in the difficulty of each task among the four groups, and that difficulty was not a factor that affected the fNIRS data.



	English Letter	Japanese Letter	English Category	Japanese Category
□ G1	3.81	3.13	7.12	5.00
□ G2	5.06	5.00	7.61	8.83
■ G3	5.07	4.57	7.14	8.14
■ G4	2.50	3.42	4.58	6.33

Figure 6. Number of words produced

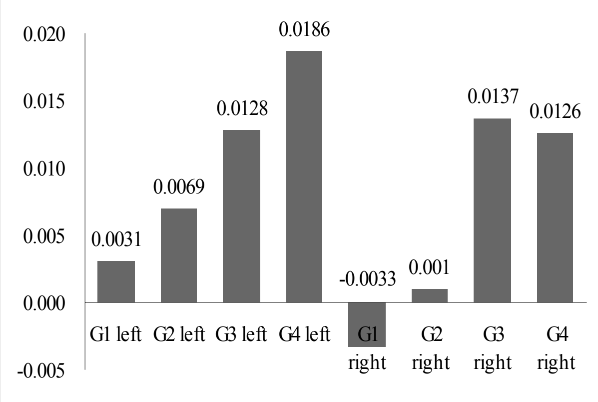


Figure 7. English letter VFT in mM-mm

3.1.2. VFT: English letter task

Descriptive data are provided in Figure 7. We carried out an analysis of variance (ANOVA) on fNIRS data in both hemispheres among four groups (F(7,139)=411.322, *p*<.001, *eta squared*=.954). The results of a post hoc Bonferroni are as follows: G1<G2<G3<G4 in Broca's area while G1<G2<G3=G4 in its right homologous area. Thus, G1 showed the least amount of brain activation in the English letter task in both hemispheres. G2 revealed the second least amount of brain activation in both hemispheres. Meanwhile, both G3 and G4 needed more brain activation than G1 and G2, irrespective of whether it was in the left or right hemisphere.

3.1.3. VFT: Japanese letter task

Figure 8 summarizes the fNIRS data on which we carried out an ANOVA (F(7,139)=50.220, *p*<.001, *eta squared*=.717). The results of a post hoc Bonferroni are as follows: G1=G3<G4<G2 in Broca's area and G1<G3<G2<G4 in its right homologous area. Thus, G1 showed the least amount of brain activation on the Japanese letter task in both hemispheres. G3 demonstrated the second least amount of brain activation in the right hemisphere and as minimal in

the amount of activation as G1 in the left hemisphere. Meanwhile, both G2 and G4 needed more brain activation than G1 and G3, irrespective of whether in the left or right hemisphere.

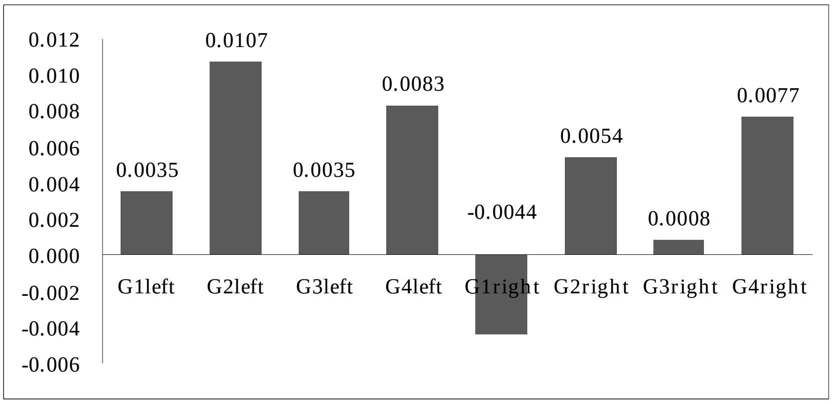


Figure 8. Japanese letter VFT in mM-mm

3.1.4 VFT: English category task

Figure 9 presents the summary of fNIRS data on which we conducted an ANOVA (F(7,139)=92.782, *p*<.001, *eta squared*=.824). The results of a post hoc Bonferroni are as follows: G1=G2, G1=G4, G3=G4, G1<G3, G2<G3/4 in Broca's area while G3<G1<G2<G4 in its right homologous area. Thus, there were few statistically significant differences in the Broca's area among the four groups while each group differed from other in the right hemisphere in the order of G3 being the least activated, then G1, G2, and G4 being the most activated.

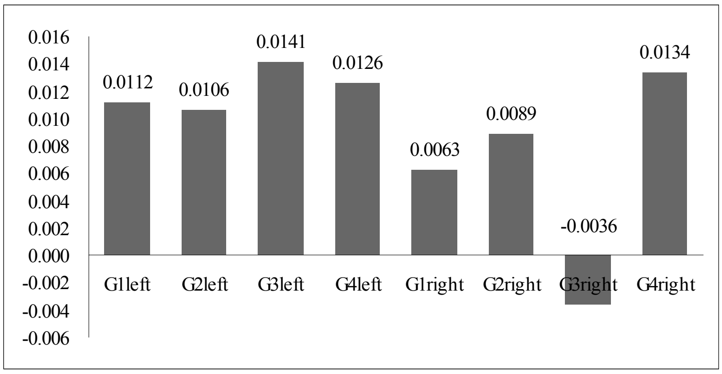


Figure 9. English category VFT in mM-mm

3.1.5. VFT: Japanese category task

The summary of the fNIRS data is presented in Figure 10. We carried out an ANOVA on the fNIRS data in both hemispheres in all the four groups (F(7,139)=148.025, *p*<.001, *eta squared*=.882). The results of a post hoc Bonferroni are as follows: G1<G3<G2<G4 in Broca's

area while G1=G2=G4, G1>G3, G2>G3/4, G3<G1/2, G4=G1/3 in its right homologous area. There is little difference among the four groups in the right hemisphere, which signifies that, regardless of OA for L2 and LOR in the L2 environment, the Japanese category task seems to activate the right hemisphere to the same degree for everyone.

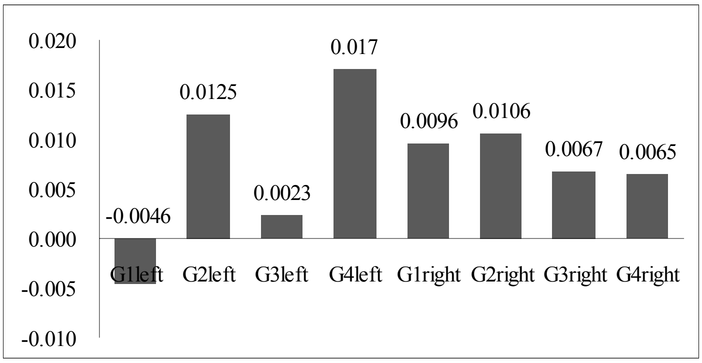


Figure 10. Japanese category VFT in mM-mm

3.1.6. VFT: summary

The results from the four tasks, particularly the L2 English tasks, are combined here in an attempt to seek the answers to our research questions.

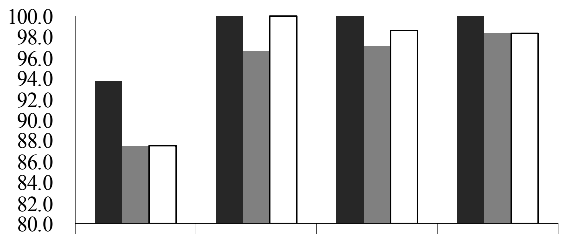
The results of the English letter task disclosed that the earlier the onset age of exposure to English and the longer that exposure lasts, the less the brain activation is observed in Broca's area in the left hemisphere. Onset age (OA) to English was important when distinguishing G1 (OA at birth) from G2 (OA before age 7) and G3/4 (OA after 12). Furthermore, English learning duration differentiated G3 with the experience of studying in an English-speaking country for from one to six years, from G4 who had received a formal English education for only six months in Japan. The second finding concerned the brain activation level in the right hemisphere which was identical to the left hemisphere except there was no statistical difference seen between G3 and G4.This can be interpreted that one to six years of study in an English-speaking country is not as sufficient for dominant use of the left hemisphere for L2 (letter fluency) processing. Thirdly, G1 and G2 (OA before 7) use Broca's area during the English letter task significantly more than the right counterpart, whereas G3 uses both hemispheres to the same degree and G4 dominantly use their left hemisphere.

The English category task showed both similar and different pictures in the results. The similar results can be seen in the right hemisphere where brain activation increased in the order of G1 (least), G2, and G3 (most). Meanwhile, a totally different tendency was observed in Broca's area where no statistical differences were found among the four groups. Previous research has found that the letter fluency task is generally more difficult and requires more brain activation than the category fluency task (e.g., Kubota *et al.,* 2005; Ehlis *et al.,* 2007). This helps us to interpret that the category task is easy enough for most L2 English learners to carry out using Broca's area (automatization possibly leads to no group differences). On the other hand, in the right hemisphere where language function is indirectly involved, brain activation is still affected by L2 proficiency in terms of OA and LOR as shown by more brain activation for G4 and the least amount for G1.

3.2. *Numeral Task*

3.2.1. Accuracy rates

The summary of the accuracy rates for each task in each group is provided in Figure 11. The average accuracy rates for each task were 98.4% for the *Bilingual Numeral Task*, 94.9% for the *English Numeral Task*, and 96.1% for the *Japanese Numeral Task*. A chi-square test revealed that there was no significant difference among the groups in the accuracy rates for the three tasks: *Bilingual Numeral Task* (χ^2=2.845, *df*=3, p>.05), *English Numeral Task* (χ^2=7.214, *df*=9, p>.05), and *Japanese Numeral Task* (χ^2=7.567, *df*=9, p>.05). The average accuracy rates for each group were 89.5% for G1, 98.8% for G2, 98.6% for G3, and 98.8% for G4, which revealed no group differences as well (χ^2=14.049, *df*=8, p>.05). This indicates no impact from the task difficulty on the fNIRS data among the groups.



	G1	G2	G3	G4
■ Bilingual	93.8	100.0	100.0	100.0
■ English	87.5	96.7	97.1	98.3
□ Japanese	87.5	100.0	98.6	98.3

Figure 11. Accuracy rate (%) for each task in each group

3.2.2. Bilingual *Numeral Task*

fNIRS data of the bilingual *Numeral Task* are summarized in Figure 12. An ANOVA showed statistical differences among the four groups (F(7,139)=972.150, p<.01, *eta squared*=.784). A post hoc Bonferroni revealed group differences of G4<G1<G2=G3 in Broca's area and G1=G3<G2=G4 in its right homologous site. At the same time, within-group analyses revealed that significantly more right hemispheric activation was seen in G1 and G4 whereas the trend was reversed in G3 and both hemispheres became activated at the same level in G2.

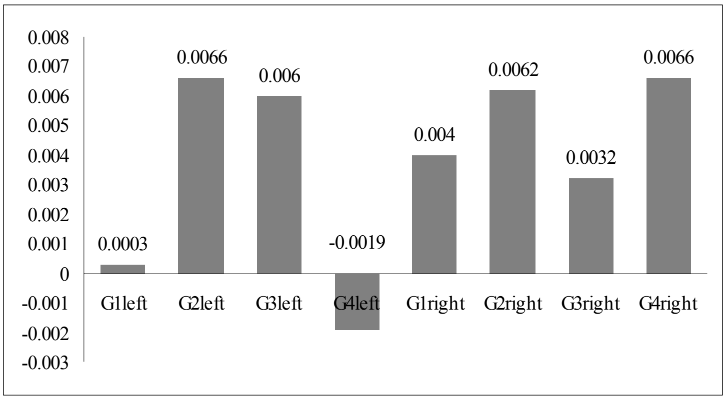


Figure 12. Bilingual Numeral Task

3.2.3. English *Numeral Task*

fNIRS data of the English *Numeral Task* are summarized in Figure 13. An ANOVA showed statistical differences among the four groups (F(7,139)=80.744, *p*<.01, *eta squared*=.803). A post hoc Bonferroni revealed group differences, G3<G1=G2<G4 in Broca's area and G3<G1=G2<G4 in the right homologous site. At the same time, within-group analyses revealed that significantly more left hemispheric activation was seen in G1, G2, and G3 whereas both hemispheres became activated at the same level in G4.

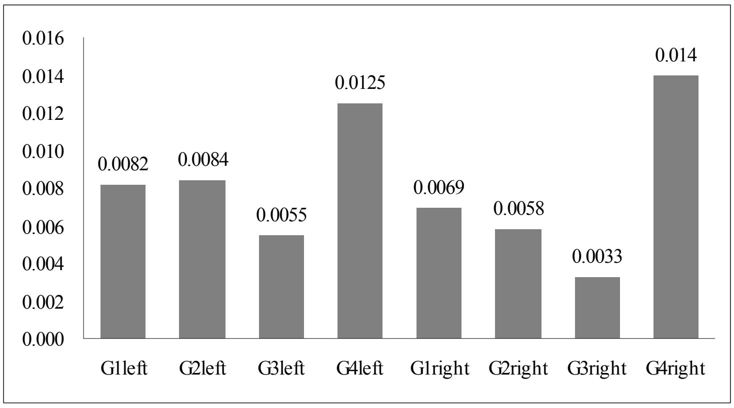


Figure 13. English Numeral Task

3.2.4. Japanese *Numeral Task*

fNIRS data of the Japanese *Numeral Task* are summarized in Figure 14. An ANOVA showed statistical differences among the four groups (F(7,139)=116.920, *p*<.01, *eta squared*=.855). A post hoc Bonferroni revealed group differences of G1=G3<G4<G2 in Broca's area and G3<G1<G2<G4 in the right homologous site. At the same time, within-group analyses revealed

that significantly more left hemispheric activation was seen in G2 and G3 whereas the trend was reversed in G1 and G4.

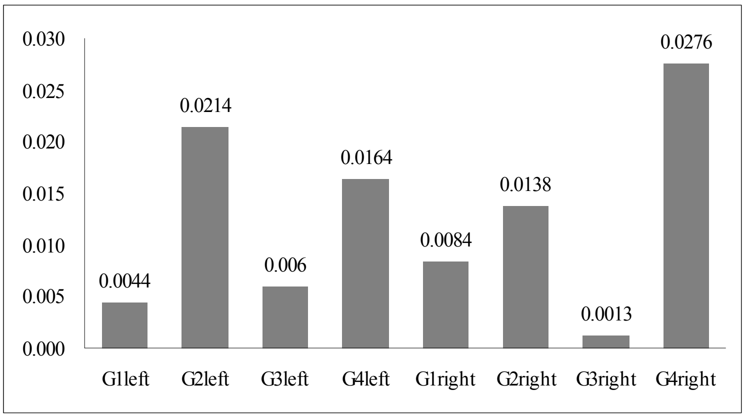


Figure 14. Japanese Numeral Task

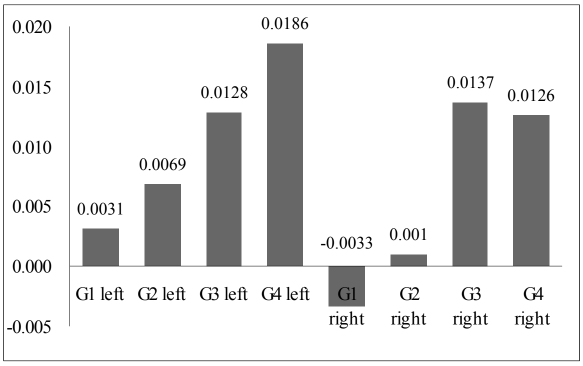
3.2.5. Numeral Task summary

Our focus is placed on the results of the bilingual and English numeral tasks since this study mainly explores the critical period for L2 acquisition. The most striking finding relates to G4's fNIRS data for the bilingual and English numeral tasks. G4 needed the most amount of cerebral blood flow on the English task in both hemispheres along with the right hemisphere on the bilingual task whereas G4 displayed the least activation in Broca's area for the bilingual task. According to Stephan *et al.* (2003), the left hemisphere of the brain is activated on letter decisions (identifying the number in the task) and the right hemisphere attends to visuo-spatial decisions (recognizing the ink colour that each number is written in). Considering the fact that L1 processing takes place in the left part of the brain, G4 must have had a hard time processing the English numeral task concurrently in both the left side of the brain (where recognition of each stimulus number and verbalizing the answer in L2 English are executed) and in the right brain hemisphere (where discrimination of the colour of each number is made, in addition to L2 processing). This difficulty revealed itself in their fNIRS data on the English numeral task. On the bilingual numeral task, however, G4 automatically processed the letter information in L1 with ease (which is seen in the least brain activation fNIRS data on the left side of the brain) and were able to process both colour identification and L2 English easily too.

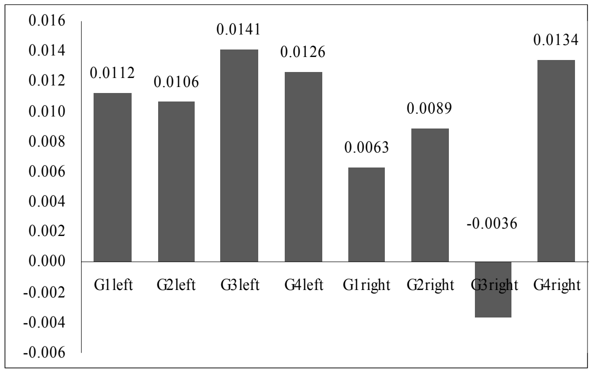
Other findings include clear differences between groups in some fNIRS data and no differences for other data. The first tendency is seen (1) in the difference between G1 and G2 and between G3 and G4 on the bilingual numeral task in both hemispheres, and (2) in the difference between G3 and G4 on the English numeral task in both hemispheres. Similarities, on the other hand, are seen between G1 and G2 for the English numeral task in both hemispheres.

4. Discussion

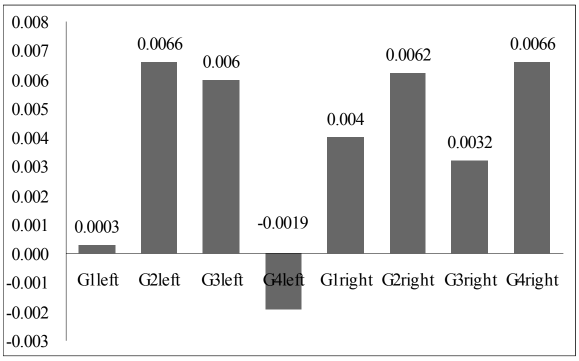
The fNIRS data relevant to our query into the critical period for L2 acquisition are presented in Figure 15 to seek the answers to our two research questions.



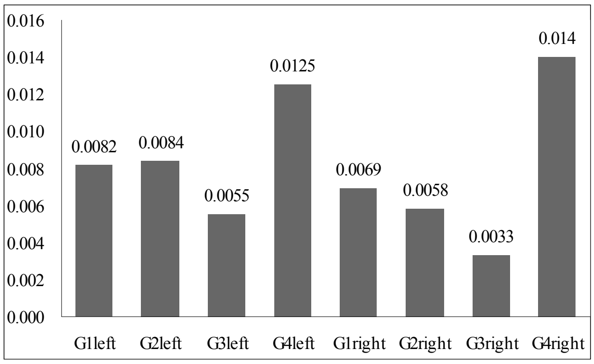
VFT: English letter



VFT: English category



Numeral: Bilingual



Numeral: English

Figure 15. Summary of English related fNIRS data

4.1 Research Question 1:

Do simultaneous bilinguals (OA at birth) show different brain activation in their L2 use when compared to sequential bilinguals (OA before the age of seven)?

The English VFT results show that G2 (OA before seven) need significantly more brain activation than G1 (OA at birth) in both hemispheres on the letter task and in the right hemisphere for the category task. The same tendency holds true for the bilingual *Numeral Task* in both hemispheres. Meanwhile, no such differences were observed in the left hemisphere on the English category task, or both hemispheres on the English *Numeral Task*.

Table 4. Comparison between G1 and G2

task	language	sub-category	hemisphere	activation	cognitive demand
VFT	English	letter	left	**G1 < G2**	✓
			right	**G1 < G2**	✓
	English	category	left	**G1 = G2**	×
			right	**G1 < G2**	×
Numeral	Bilingual		left	**G1 < G2**	✓
			right	**G1 < G2**	✓
	English		left	**G1 = G2**	×
			right	**G1 = G2**	×

(= indicates no statistical differences)

The overall picture reveals that G2 needed to activate their brain areas as much as or more than G1 for all four tasks. A more accurate picture, however, manifests itself with a closer look at the data considering the cognitive demand perspective of the tasks. Izzetoglu *et al.* (2004) and Stephan *et al.* (2003), who used VFT tasks in their brain-imaging experiments, reported that the letter task was more demanding than the category task. In addition, for the numeral task, the bilingual version is obviously more demanding than the English task in that participants must function in the dual language mode while they only needed to attend to a single language in the latter task. In the more cognitively demanding (*VFT* letter and bilingual *Numeral*) tasks, the G1 activation level was significantly lower than their counterparts (Figure 16). In the relatively less demanding (the *VFT* category and the English *Numeral*) tasks, the G2 activation level was similar to G1's. Thus, it appears that we can validly conclude that the onset age of L2 exposure at birth results in less brain activation in both hemispheres than participants with the onset age of L2 exposure before age seven, which is observable particularly on cognitively demanding tasks.

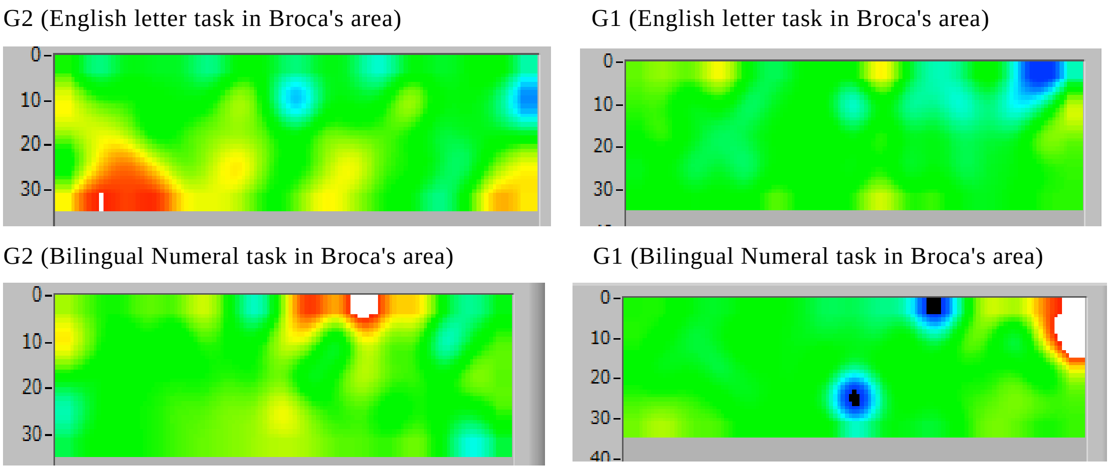


Figure 16. Oxy-Hb comparison (red indicates high activation while blue indicates least activation)

4.2 Research Question 2:
Is the length of exposure to L2 important in brain activation when the L2 is learned after the critical period?

This research question is an attempt to seek an answer to our query as to whether or not brain activation changes as L2 proficiency improves in those who are first exposed to an L2 at age 12 - after the critical period for language learning. Table 5 summarizes the fNIRS data comparing G3 to G4. G3 has the experience of one to six years of intensive and extensive exposure to English by studying in an English-speaking country. G4 had only a six-month formal English education in Japan with no overseas experience before they participated in this experiment.

Table 5. Comparison between G3 and G4

task	language	sub-category	hemisphere	activation	cognitive demand
VFT	English	letter	left	**G3 < G4**	✓
			right	**G3 = G4**	✓
	English	category	left	**G3 = G4**	×
			right	**G3 < G4**	×
Numeral	Bilingual		left	**G3 > G4**	✓
			right	**G3 < G4**	✓
	English		left	**G3 < G4**	×
			right	**G3 < G4**	×

(= indicates no statistical differences)

A similar picture can be seen, as in RQ1, although not in terms of the L2 onset age but connected to the L2 learning duration: The longer the study time, the less the brain activation that occurred as was seen in 63% of the tasks. In addition, G4 showed the same degree of brain activation as G3 in 25% of the tasks. Both ratios were calculated including both cognitively non-demanding and demanding tasks. Thus, 88% of the tasks were accounted for in this manner.

However, there is one instance when comparing G3 to G4 when the data did not follow this argument. Here, when examining the fNIRS data on the left side of the brain on the bilingual *Numeral* task, G3 exhibited more blood flow than G4 (highlighted in Table 5). In this task, the participants were instructed to say the numbers aloud either in Japanese or English, depending on the ink colour of the numbers displayed on the computer monitor. One possible interpretation for the low fNIRS signals in G4 could be that they had to pay so much attention to the ink colour, activating the visuo-spatial faculty in the right anterior cingulate cortex and right parietal areas, as well as their L2 in the right hemisphere, that they had little resources left for L1 processing in the left side of the brain.

Another interpretation of the fNIRS data can be made by examining the low brain activation in the left hemisphere, in G1 and G4 on the bilingual *Numeral* task. As far as English proficiency is concerned, the participants' language background information based on OA and L2 exposure duration predicts that G1 would be the most proficient followed by G2, G3, and G4. The fNIRS data, however, do not reflect the prediction of G1 having the least brain activation and G4 the highest, but the data show more activation in G2 (OA<7) and G3 (OA=12, L2 sojourn for one to six years) than G1 (OA=0) and G4 (OA=12, duration=6 months). G1 aside, this tendency of more proficient L2 learners in G2 and G3showing more activation in Broca's area, than the novice learners in G4 could be due to a combination of the timing of exposure to L2 and the foundation of their L1. G1 participants developed both their languages simultaneously from birth and G4 had a solid L1 foundation before they began to learn English at the age of twelve. Meanwhile, G2's first intensive and extensive exposure to English began before seven, when their L1 had not yet been fully developed, and G3 underwent such experiences in their teens or twenties when their L2 needed fine-tuning. Thus, the significantly higher brain activation in G2 and G3 than G1 and G2 could be caused by an interruption to their L1 development in their teens and twenties.

Regardless of how valid our interpretation may be, the general tendency observed here leads us to conclude that, the longer the exposure to L2, the less is the brain activation in both hemispheres, irrespective of whether the tasks involved are cognitively demanding or not.

5. Conclusion

The present study used a linguistic *Verbal Fluency Task* as well as a more cognitively demanding *Numeral Task* to examine brain activation in relation to the critical period for language acquisition and L2 learning duration. The results first demonstrated that the earlier one's first intensive and extensive exposure to an L2 is, the less brain activation is shown in both hemispheres, even in those exposed to L2 before the critical period. This suggests that L2 processing requires less energy in the brain when exposure to the language takes place earlier on in life. The second finding revealed that brain activation lessens in both hemispheres as L2 proficiency improves, implying that one needs less energy in L2 processing as L2 learning extends in time. In addition, an incidental finding hinted at a need to firmly solidify L1 without the interruption of L2 acquisition or learning while still fine-tuning the L1 in the teens and twenties.

This study is not without its limitations. To confirm our conclusion, further research is needed to see if the results are due to a longer language exposure or the interplay of the longer duration and the impact of being immersed in an L2 community (G3, in particular, included only those who have studied for some time in an English-speaking country). Secondly, more participants of a similar age in the different groups are needed to eliminate an intervening variable such as maturation, which could have affected the results. In addition, a longitudinal study to further examine the L2 novice learners, could lend support to our tentative conclusion in this study.

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