Examining Bilingual Language Processing, Using both Physiological and Conventional Linguistic Approaches

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[Abstract]

The present study was undertaken to find answers to the research question of how collecting both linguistic and physiological (fNIRS, EEG, and eye-tracking) data contributes to capturing a better picture of bilingual language processing. Linguistic (spontaneous oral and written) and three types of physiological (fNIRS, ERP, and eye-tracking) data were collected from an early Japanese-English bilingual. The linguistic data analysis displayed similarities (i.e., speech ratio and story grammar) and differences (i.e. preferred pause types) between the two languages. The writing data revealed high writing proficiency both in the sub-components and overall Quotient score. The code-switching tasks were able to successfully identify which parts of the brain (the right hemisphere) are more activated and when such activation takes place (more negativity earlier on but more positivity later on). Eye-tracking data analysis revealed more time was needed to interpret GP sentences which in turn induced less stops on each word in such sentences in comparison with Non-GP sentences. Thus, it is suggested that a linguistic and physiological data combination can better contribute to capturing a fuller picture of bilingual language processing than just conventional linguistic or physiological research methods alone.

Keywords : bilingual, brain, fNIRS, ERP, eye-tracking

1. Rationale

Bilingual research has conventionally collected linguistic data alone to describe what is different in language behavior in bilinguals compared to monolinguals. With the advent of neuro-imaging data technology, however, scholars such as Andrews (2019) and Steinhauer & Kasparian (2020) reiterate the importance of neurolinguistic data in combination with linguistic/behavioural data. They base their argument on the premise that the same level of language proficiency does not necessarily result in a similar level of brain activation. To date, there seems to be only one study which has longitudinally examined acquisition and attrition by collecting both linguistic (receptive phonological sensitivity) and neurolinguistic (ERP) data (Ostenhout *et al,* 2019). This study tested

16 university students in the US learning Finnish after nine months acquisition, then they were tested again for attrition nine months after the termination of their classroom instruction. The results lend support to the Complex Dynamic Systems Theory (Larsen-Freeman, 2017) in that language acquisition and attrition is systematic and linear but at the same time adaptive and variable in nature. Regarding this variability, a question arises as to whether Ostenhout *et al*'s results can also be observed in languages naturally acquired, particularly in production since they only targeted a school-learnt language by collecting receptive data. In pursuing answers for this enquiry, the present study attempts to collect both behavioural (linguistic) and physiological data from bilinguals who have acquired two languages in natural settings. In collecting physiological data, we use fNIRS (functional Near-Infrared Spectroscopy) and an eye-tracking apparatus along with an EEG device in an attempt to capture a fuller picture of bilingual language production.

Research question: *Does collecting both linguistic and physiological (fNIRS, EEG, and eye-tracking) data contribute to capturing a fuller picture of bilingual language processing?*

2. Method

2.1 Participant

An early Japanese-English male bilingual participated in this research. He was born in an international family with his mother being an English native speaker and his father a Japanese native speaker, and has spent most of his life in Japan, attending local kindergarten, primary school, high school, and university, apart from two prolonged periods in Australia when he was in the 4th and 9th grades for 2.5 years. Upon graduating from university, he took an English-Japanese interpreting job. Linguistic and physiological data described below were collected when he was 36 years old and had worked as an interpreter for 13 years. Prior to the data collection, the participant signed a written consent form and was given a book voucher for his participation.

2.2 Procedures and data analysis

Spontaneous oral and written data in English and Japanese were collected to tap into the participant's on-line linguistic processing. The wordless picture book "*Frog, where are you?*" (Mayer, 1969) was used as a prompt to collect oral data (Figure 1). After going over the book to familiarize himself with the plot, the participant was asked to orally narrate the book without any time limit. The collected oral data were transcribed and analyzed for fluency, accuracy, and story grammar. For spontaneous written data, *the Test of Written Language-3* (TOWL-3, henceforth) devised by Hammill & Larsen (1996) was used (Figure 2). The participant was given 15 minutes to write an English story on a picture. The written data were assessed by the scoring criteria provided by the test in terms of contextual conventions (basic English writing rules), contextual language (lexical and morphosyntactic accuracy), and story construction (impact on readers). The sum of

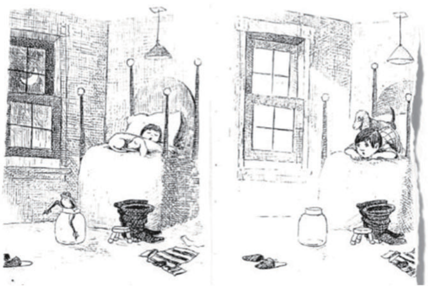

Figure 1. *Frog, where are you?*

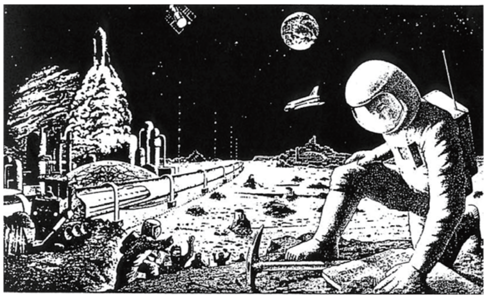

Figure 2. TOWL-3

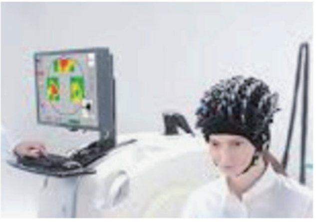

Figure 3. fNIRS
(Shimadzu web site)

Figure 4. EEG
(CGX web site)

Figure 5. Eye-tracker
(Tobii web site)

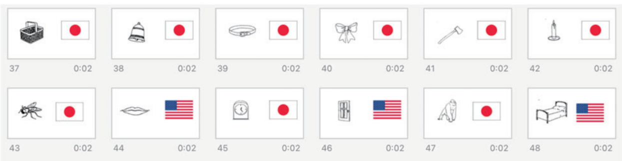

Figure 6. Code-switching task for fNIRS

Figure 7. Code-switching task
for EEG

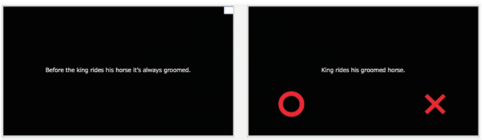

Figure 8. Non garden-path sentences

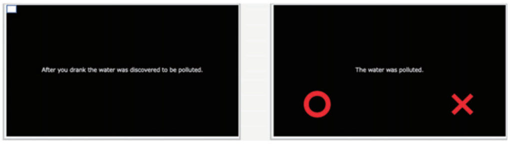

Figure 9. Garden-path sentences

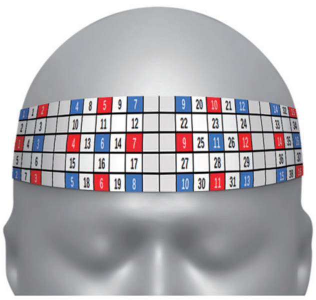

Figure 10. fNIRS probes

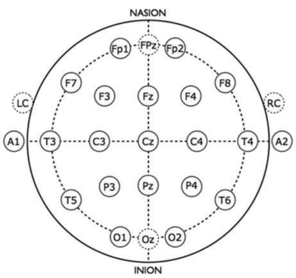

Figure 11. EEG electrodes

the raw scores was converted age-appropriately to make it possible to compare the score against monolingual norms in English.

To collect the physiological data, a 42-channelled Shimadzu 3000 fNIRS (functional Near-Infrared Spectroscopy, Figure 3), a 19-channelled CGX Quick 20-r EEG (Figure 4), and a Tobii Pro Fusion eye-tracker (Figure 5) were used to collect hemoglobin concentration data (115 Hz), ERP brain oscillations (500 Hz), and eye-movement (250 Hz), respectively. Two types of code-switching tasks were used as prompts to see which part of the brain is activated (fNIRS) and when such activation takes place (EEG). Hemoglobin (fNIRS) and ERP oscillation (EEG) signals were monitored when the participant was working on the tasks: i) A picture with a flag was presented every 2.5 seconds prompting the participant to orally name the item in the language indicated by the flag (a total of 84 slides) as seen in Figure 6 (the picture card of a 'fly' beside a Japanese flag requiring him to say 'HAE' while the 'mouth' picture card with an American flag beside it required him to say 'mouth'), and ii) A word was presented every two seconds requiring him to say the original word aloud or the translation of the word (the EE 'peanut' card asking him to say 'peanut' while the EJ 'pig' card, asking him to say 'BUTA') as shown in Figure 7. A total of 132 slides were randomly presented.

In addition, eye-tracking data were obtained when the participant engaged in reading either non-garden-path sentences (five syntactically simple and straightforward sentences as shown in Figure 8, Non-GP) or garden-path (GP) sentences (five syntactically complex or ambiguous sentences as seen in Figure 9). Each slide was presented for six seconds before a true or false question slide appeared on the screen where he was asked to fix his gaze on either the answer true (a red circle) or false (a cross). A total of ten sentences were randomly presented on a PC screen.

In analyzing the fNIRS data (mMmm), the raw data first underwent the procedures of standardizing them and then subtracting the rest task (a series of six consecutive Japanese naming tasks) data from the CS task data to make an intra-personal task comparison possible. The Oxygenated Hemoglobin (Oxy-Hb) is used to represent the fNIRS data (Oxy-Hb, Dexoy-Hb, and Total-Hb) in this study (Fukuda, 2009). Out of the 42 channels, we placed a special focus on five bilateral brain regions – the Anterior Cingulate Cortex (ACC), the Inferior Frontal Gyrus (IFT), the Dorsolateral Prefrontal Cortex (DLPFC), the pre-Supplemental Motor Area (pre-SMA), and the Supra-marginal Gyrus (SMG). This focus is based on literature targeting bilingual code-switching behavior to examine cognitive conflicts in the ACC, productive speech in the IFG (Broca's area), information retention and planning in the DLPFC, new learning in the pre-SMA, and phonological working memory in the SMG.

The *BrainVison Analyzer 2.2* software (Brain Products) was used to analyze the ERP raw data taken from 19 channels (Figure 11) with a time window of -100 to 800 ms. Considering the linguistic nature of the current study (*e.g.*, Delogu, Brouwer, and Crocker, 2021; Kotz, Frisch, and Friederici, 2024.), we placed a special emphasis on three types of data - ELAN (early left anterior negativity, 200ms), LAN (left anterior negativity, 300-500 ms), and P600 (mostly centered in the Parietal lobe).

Our area of interest in analyzing the eye-tracking data focused on the four to five words in the middle of each sentence which differentiate Non-GP sentences from GP sentences as seen in the examples of 'Before the king *rides his horse it's* always groomed' in Figure 8 and 'After you *drank the water was discovered* to be polluted' in Figure 9. Using the *Tobii Pro Lab 1.181* software, the average eye fixation durations (ms) and fixation counts were calculated for each condition.

3. Results

3.1 Linguistic data

3.1.1 Spontaneous productive (oral narrative) data

Out of the original narrative data provided by the participant, two excerpts of the English and Japanese transcription of the frog story are provided here.

English: ..... *Seeing that, the frog climbed out of the glass jar. The boy and dog were surprised in the morning to find that the glass jar in which they'd left the frog was empty.....*

Japanese: *..... 少年と犬が寝静まった頃，蛙はそっとガラス瓶を抜け出して少し開いていた窓から外に逃げました .....*

(Shonento inuga neshizumattakoro, kaeruwa sotto garasubinwo nukedashite sukoshiaiteita madokara nigemashita)

Oral fluency analyses are summarized in Table 1 which shows both similarities (almost an identical speech ratio out of the total task duration – 53 to 56%) and differences (longer intra-sentential pause duration in English but longer inter-sentential pause duration in Japanese). The story grammar analysis (Table 2) clearly exhibits that the participant always mentioned the story setting along with all eight episodes (characters, problems, and consequences) both in English and Japanese. The accuracy analysis reveals no mistakes in either language.

Table 1. Oral fluency

	English	Japanese
TotalTaskDuration (ms)	361,960	386,505
TotalPauseDuration (ms)	170,274	169,093
TotalSpeechDuration (ms)	191,686	386,505
Speech (%)	53.0	56.3
#TotalSentences	39	34
#TotalPause	128	191
#InterSententialPause	38	33
#IntraSententialPause	90	158
AveIntraSententialPause (ms)	2,122.5	740.8
AveInterSententialPause (ms)	995.8	1,577.0

Table 2. Story grammar

Episode	English	Japanese
setting	✔☐	✔☐
1st	✔☐	✔☐
2nd	✔☐	✔☐
3rd	✔☐	✔☐
4th	✔☐	✔☐
5th	✔☐	✔☐
6th	✔☐	✔☐
7th	✔☐	✔☐
8th	✔☐	✔☐

3.1.2 Spontaneous productive (written) data

An excerpt from the writing task is supplied first to give context to the results.

This is the drawing which Elon Musk used to convince angel investors to finance the business which later would become known as Space X. As you can see, there is nothing too special about the drawing. Musk most likely cut it out of a pulp fiction comic back from the 80s – who knows.....

When examining the participant's writing, the TOWL-3 scores in the contextual conventions, contextual language, and story construction are 12, 13, and 14 respectively (scores between 8 and

12 are average for the same age group in North America). The Quotient score is 120 while the average score for the same U.S age group is set between 90 and 110. This signifies that the participant's English writing proficiency is within or above his monolingual counterparts in terms of three sub-components and the overall scores. There is no such writing test available in Japanese, therefore no data could be collected to assess his Japanese writing skills.

3.2 Physiological data

3.2.1 fNIRS data

An analysis of variance was conducted ($F(29,101)=63.211$, $p<.001$, *Eta Squared* =.0.948) with a post-hoc Bonferroni for an intra-personal comparison. The tasks included naming pictures in Japanese, English, and then code-switching. Ten brain regions including the bilateral ACC, IFG, DLPFC, pre-SMA, and SMG were examined.

Categorizing the fNIRS values (mMmm) reveals that the brain becomes significantly more activated in the right hemisphere than in the left hemisphere when the participant engages in the code-switching task in comparison to the monolingual tasks, (Table 3 and Figure 12). The right hemispheric involvement seems to be more acute in code-switching.

3.2.2 ERP data

When analyzing the ERP data, the variance was examined in four tasks given to the participant. The first task was a Japanese word to be repeated in Japanese (JJ) as see in Figure 16. Then an English word needed to be repeated in English in the second task (EE) as seen in Figure 15. In task 3, a Japanese word was translated into English by the participant as seen in Figure 14 (JE). Finally, task 4 was an English word to be translated into Japanese as seen in Figure 13 (EJ). These tasks were carried out, using P600 and ELAN/LAN analysis.

The P600 analysis ($F(3,223)=143.783$, $p<.001$, Eta Squared=0.659) revealed a significantly higher positivity for the JJ task followed by EE, JE, and EJ. On the other hand, the ELAN/LAN analysis ($F(3,221)=291.613$, $p<.001$, Eta Squared=0.975) showed that the significantly lowest negativity was observed in JJ, followed by EE and EJ=JE. The results together indicate that the ERP signals derived from code-switching (JE or EJ) are distinctively different time-wise from those derived from monolingual tasks (either JJ or EE) in that more positivity is induced by monolingual tasks as opposed to the code-switching tasks, being presented first up to 350 ms from the task onset. More negativity was induced by the code-switching tasks than monolingual tasks, being manifested as P600 signals.

Table 3. The fNIRS data comparison

	Tasks (languages)					Brain region			Hemisphere	
0.60 < fNIRS (mMmm)										
IFGcsR	CS			IFG					right	
0.40 < fNIRS < 0.60										
IFGeL		Eng		IFG						left
ACCjL			Jpn		ACC					left
ACCjR			Jpn		ACC				right	
DLPFCeR		Eng				DLPFC			right	
DLPFCjL			Jpn			DLPFC				left
DLPFCcsR	CS					DLPFC			right	
preSMAjL			Jpn				preSMA			left
preSMAjR			Jpn				preSMA		right	
SMGeL		Eng						SMG		left
SMGcsR	CS							SMG	right	
0.20 < fNIRS < 0.40										
IFGeR		Eng		IFG					right	
IFGcsL	CS			IFG						left
ACCeR		Eng			ACC				right	
ACCcsR	CS				ACC				right	
preSMAeR		Eng					preSMA		right	
0.20 > fNIRS										
IFGjL			Jpn	IFG						left
IFGjR			Jpn	IFG					right	
ACCeL		Eng			ACC					left
ACCcsL	CS				ACC					left
DLPFCeL		Eng				DLPFC				left
DLPFCjR			Jpn			DLPFC			right	
DLPFCcsL	CS					DLPFC				left
preSMAeL		Eng					preSMA			left
preSMAcsL	CS						preSMA			left
preSMAcsR	CS						preSMA		right	
SMGeR		Eng						SMG	right	
SMGjL			Jpn					SMG		left
SMGjR			Jpn					SMG	right	
SMGcsL	CS							SMG		left

Figure 12. Hemispheric distribution of fNIRS data

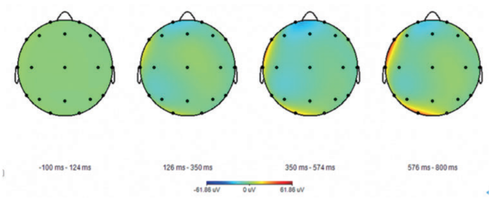

Figure 13. ERP data for EJ task

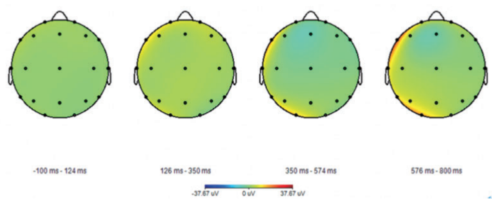

Figure 14. ERP data for JE task

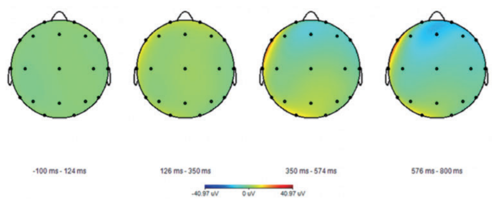

Figure 15. ERP data for EE task

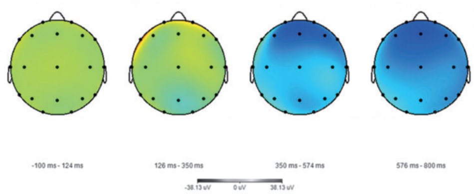

Figure 16. ERP data for JJ task

3.2.3 Eye-tracking data

Eye-tracking data were collected while the participant was silently reading five GP and five Non-GP sentences that were randomly presented every six seconds followed by T/F questions. The average fixation durations on the four to five focal words in the middle of the sentences were 160 ms in the Non-GP sentences which was a shorter length of time than 220 ms in the GP sentences. The average eye fixation counts in the Non-GP sentences were 17 while they were only 10 in the GP sentences. Eye-tracking data visualizations are presented in Figures 17 and 18. The analysis appears to indicate that processing complex GP sentences takes longer time on focal words, which in turn does not allow the reader to stop as often as they can in reading simple Non-GP sentences.

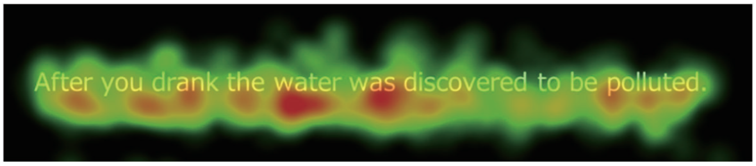

Figure 17. Eye-tracking data visualization in a GP sentence

Figure 18. Eye-tracking data visualization in a Non-GP sentence

4. Discussion

The present study was undertaken to find answers to the research question of '*Does collecting both linguistic and physiological (fNIRS, EEG, and eye-tracking) data contribute to capturing a fuller picture of bilingual language processing?'* The data included linguistic (spontaneous oral and written) data along with three types of physiological (fNIRS, ERP, and eye-tracking) data. The data analysis on the spontaneous oral data in English and Japanese showed similarities (i.e., speech ratio and story grammar) and differences (i.e. preferred pause types) between the two languages. The TOWL-3 scores revealed high writing proficiency both in sub-components and the overall Quotient score, which are either average or above average when compared to the participant's monolingual counterparts in English. The code-switching tasks were able to successfully identify which part of the brain (the right hemisphere) is more activated and when such activation takes place (more negativity earlier on but more positivity later on). The eye-tracking data analysis showed that more time was needed to interpret complex GP sentences, which in turn induced less stopping at each word in comparison to simple Non-GP sentences. Thus, it is suggested that combining both linguistic and apparatus-based physiological data can better contribute to capturing a fuller picture of bilingual language processing than the conventional linguistic or physiological research methods. However, in order to confirm this statement, many more participants are needed for data collection in the bilinguals' two languages, using similar tasks to this exploratory research.

Acknowledgements

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日本語論題

バイリンガル研究における近赤外分光法・脳波・眼球運動データの有用性検証研究

日本語要旨

本研究の目的は，バイリンガル対象の研究に言語データだけでなく近赤外分光法 (fNIRS)・脳波 (ERP)・眼球運動データ等の生体データも同時に収集することで，バイリンガル言語プロセスの核心に迫ることができるのかどうかを検証することである。早期均衡日英バイリンガル通訳者１名対象に，産出言語データとして即興ナラティブ・書記データを収集し，同時にコードスイッチタスク遂行中の fNIRS 及び ERP と袋小路文読解中の眼球運動データを収集した。分析の結果，fNIRS データは賦活脳部位を，ERP データはどの段階で脳賦活が発生したのかを同定することができ，異なる種類の生体データ併用の利点が浮かび上がった。本研究は探索的であるので，今後は対象者を増やし，各収集データの更なる細かな分析を行うことが必要ではあるが，生体データを言語データと同時収集することで包括的にバイリンガル言語処理を理解できる可能性が示唆された。

日本語キーワード

バイリンガル，脳，近赤外分光法，脳波，眼球運動