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「バイリンガル fNIRS 言語脳科学プロジェクト」研究報告

Executive Control in Japanese-English Bilingual Kindergartners in Comparison to Monolingual Japanese Children: A Neuro-cognitive Study

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Abstract

This study explores if bilingual children demonstrate any differences in their cognitive performance compared to their monolingual counterparts. Nine children (ages 2 to 6) from a Japanese-English bilingual kindergarten in Singapore and nine children (ages 2 to 6) from a Japanese monolingual kindergarten took part in this study. The children undertook both a Simon Task and a Stroop Task individually and both behavioural and brain activation data (Fp1 and Fp2 in the Rostrolateral prefrontal cortex, RLPFC) were collected. The data are compared between the corresponding age groups, examining accuracy, reaction time, and brain activation (fNIRS values of mM-mm). The results partially lend support to a bilingual advantage in the Fp1 area of the brain in the 3, 4, and 5 year-old age groups.

Keywords : *bilingual, executive control, inhibitory control, cognition, fNIRS*

1. Introduction

Bilingual advantage in cognitive functions (executive control) has been intensely debated to date but no decisive conclusion has been drawn as yet. On one hand, supportive evidence has been reported by a number of researchers such as DeLuca, Rothman, Bialystok, and Pliatsikas (2020), Kroll and Bialystok (2013), and Parani and Abutalebi (2015). On the other hand, counter evidence has also been put forth by a number of researchers (e.g., Antón, Duñabeitia, Estévez, Hernández, Castillo, Fuentes, Davidson and Carreiras, 2014; Paap, Johnson and Sawi 2015). Some researchers have attempted to explain these discrepant results by examining the task types. Stins *et al.* (2005), for instance, contend that not all the cognitive tasks that require participants to exert inhibitory control make use of the identical neural network in the brain. Positing that multiple tasks are needed to observe bilingual language processing, Paap and Grenberg (2013) used four types of tasks only to find that bilingual advantage was very limited. To be more specific, Bialystok and Barac (2012) argue the importance of tasks used in research because bilinguals seem to be better than monolinguals at language control, not language analysis. Apart from the task type issue, Bialystok and Barac additionally make the point that the linguistic distance of the two languages used by a bilingual need to be taken into consideration and the majority of studies target bilinguals who use two languages closely linked to each other - mostly Indo-European alphabetical languages. Meanwhile, Leivada *et al.* (2020; 10) shed a unique light on "an initial publication bias that disfavours null or small-size results in the context of a newly explored hypothesis", by pointing to an upsurge in the number of studies since 2014 that do not find any bilingual advantage.

Taking the points mentioned by these researchers into consideration, Taura *et al.* (2014) targeted 79 Japanese-English bilingual (a combination of logographic and alphabetical languages) and 25 Japanese monolingual kindergartners who attempted three types of cognitively demanding tasks (Moving Word, Simon, and Stroop tasks). The results are very mixed, showing more monolingual than bilingual advantage both in speed and accuracy. One possible reason for such inconclusive results could be that 'bilingual' was simply defined as being in an English-Japanese kindergarten, that is, Taura *et al.* (2014) failed to rigidly control how long the children had been in the bilingual environment. This precise point is mentioned by Leivada *et al.* (2020;10) as a roadmap for further work who suggest "the need for laying out a solid methodology to correctly characterize the intricacies of bilingual experience and knowledge."

Thus, the research question in the present study is put forth to rectify the shortcomings of Taura *et al.*'s previous study (2014).

Research question

Do Japanese-English bilingual kindergartners have better inhibitory control than their Japanese monolingual counterparts?

2. Method

2.1 Participants

Twenty eight Japanese-English kindergartners in Singapore and twenty five Japanese monolingual children in Japan initially took part in this study. In order for the children to be matched equally between the two groups (as suggested by Leivada *et al.*, 2020), a four-step screening was undertaken. Language use and exposure was the first to be looked at. Through the language background information taken from their parents, only bilingual children whose family language is Japanese and who are daily exposed to English at kindergarten were chosen. The monolingual children in comparison, had no previous experience of receiving any English lessons nor had they lived in an English-speaking country. The second step involved the children's recognition of *HIRAGANA* (Japanese alphabet letters), followed by the third step of matching the chronological age. Lastly, for the bilingual children, we checked how long they had attended the bilingual kindergarten so that they could be labeled as 'bilingual'. Using this stringent method of matching, the two groups ended up with only nine children in each group as summarized in Table 1.

Table 1. Participants

Class		Monolingual	Bilingual (*period)
2-year	*n*	1	1
	letter recognition	0%	0%
	chronological age	2;08	2;10 (0.10)
3-year	*n*	2	2
	letter recognition	0%	0%
	chronological age	3;07	3;05 (1.04)
4-year	*n*	2	2
	letter recognition	100%	85%
	chronological age	4;10	4;05 (2.02)
5-year	*n*	2	2
	letter recognition	100%	100%
	chronological age	5;09	5;06 (3.02)
6-year	*n*	2	2
	letter recognition	100%	100%
	chronological age	6;07	6;05 (3.01)

*indicates how long they have attended the bilingual kindergarten

All the participants were recruited through each kindergarten with written parental consent, and the research took place at the individual kindergartens they attended.

2.2 Procedure

Each child was individually tested on their Japanese letter recognition, then continued on performing the Simon and Stroop tasks on a MacBook Pro 13" computer. For the Simon Task, they were instructed to press the "A" key on the keyboard when they saw a blue square on the screen and to press the "L" key with a red square cue. The congruent condition where the blue squares appear on the left side of the screen (both the blue square cue and the "A" key physically on the same left-hand side) is expected to induce a faster and more accurate response than the incongruent condition where the blue square appears on the right side of the screen. After a few trials, four congruent slides and four incongruent slides were randomly presented on the screen while response time and pressed keys (for accuracy) were recorded using the software *SuperLab*.

In the Stroop Test, the children were instructed to verbally say the ink colour of the letter aloud that was presented on the computer screen: (1) the congruent condition was where they said " あお (blue)" when they saw " あお " written in blue ink on the screen, and (2) the incongruent condition was where they had to say " あお " when they saw " あか (red)" written in blue ink. Thus, the children needed to pay attention to the ink colour alone and ignored the meaning of the letters presented on the screen (3 congruent and 7 incongruent letters).

For both the Simon and Stroop tasks, the incongruent conditions are cognitively more demanding than the congruent conditions, therefore slower response times and less accuracy were expected on the incongruent as opposed to the congruent conditions.

While the children were carrying out the tasks, two probes (a bandage size, *Dynasense pocketNIRS*) were placed on their forehead (Fp1 on the left and Fp2 on the right, using Jasper's (1958) International 10/20 system) to monitor oxygenated blood (Oxy-Hb) flow with higher values indicating difficulty.

2.3 Data analysis

Both the reaction time and the keys the children pressed were recorded using *SuperLab* for the Simon Task, and for the Stroop Test their response was recorded on an IC recorder and the reaction time was recorded on *SuperLab*. For the accuracy analysis, the *SuperLab* data were examined and the recorded sound files collected from the Stroop Test were checked.

Firstly, the fNIRS (functional Near-Infrared Spectroscopy) data were standardized. Then, the data collected when they were working on the randomized mixture of congruent and incongruent slides were subtracted from the trial performance data under congruent conditions. This is the standard procedure for the analysis of brain activation data to make a within-/between-subjects comparison possible.

The data collected from individual children aged three to six were averaged, which was not necessary for the two-year olds because there was only one participant in both the monolingual and bilingual groups. Two ANOVAs were conducted for a within-group comparison showing any developmental changes in the bilingual group and the monolingual group, and five sets of t-tests were carried out to compare the monolingual and bilingual children from each age group.

3. Results

Statistical analyses were only carried out on the brain activation data due to the limited number of participants in this study.

3.1 Behavioural data

The accuracy and reaction times observed during both the Simon Task and Stroop Test are summarized in Table 2 and Figures 1 to 8. The literature supporting the bilingual advantage (as mentioned in section 1) predicts the bilingual children will perform the two tasks under the incongruent conditions (cognitively more demanding) faster and more accurately than their monolingual counterparts.

Table 2. Behavioural data summary

tasks	Simon Task			Stroop Test		
groups	monolingual	bilingual	average	monolingual	bilingual	average
accuracy (%)			**83.9**			**95.0**
congruent	78.0	95.0	86.5	100.0	100.0	100.0
incongruent	80.0	82.5	81.3	94.3	85.7	90.0
reaction time (msec)			**2108.0**			**3017.6**
congruent	1783.7	1864.3	1824.0	2697.5	2729.2	2713.3
incongruent	2138.7	2645.1	2391.9	3108.6	3535.2	3321.9

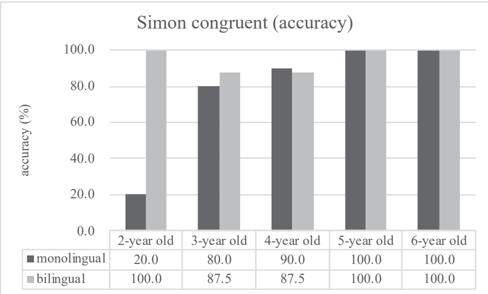


Figure 1. Simon congruent (accuracy)

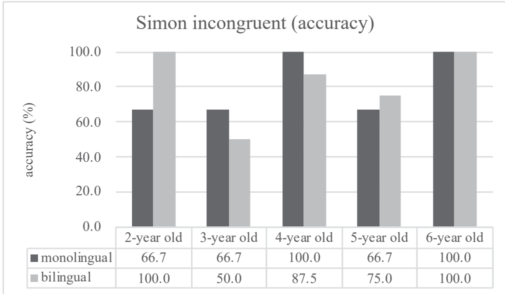


Figure 2. Simon incongruent (accuracy)

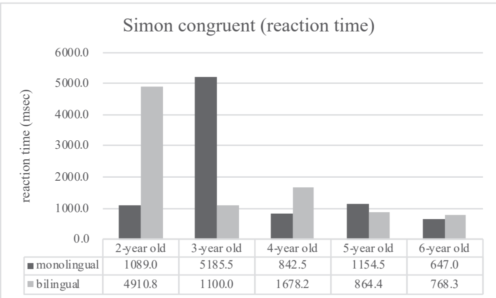


Figure 3. Simon congruent (reaction time msec)

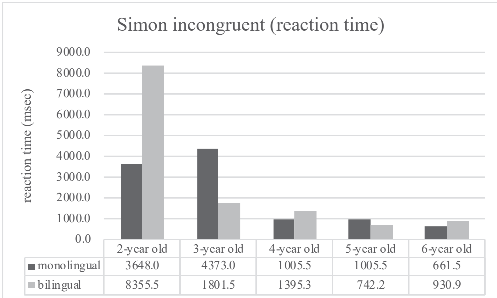
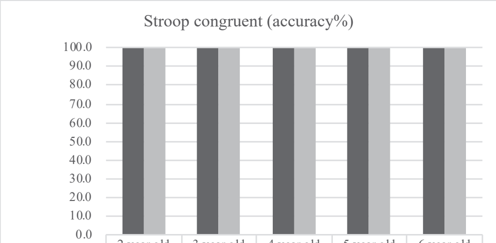


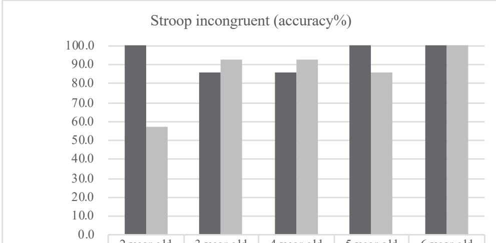
Figure 4. Simon incongruent (reaction time msec)

There was an overall tendency for the children to perform faster and with more accuracy, the older they became in both tasks, except for the accuracy rate in the Stroop Test where there was a 100% accuracy rate. A closer look at the accuracy rates reveals that the children performed better in the Stroop Test (95.0%) than for the Simon Task (83.9%) but their reaction time was faster in the Simon Task (2,108.0 msec) than in the Stroop Test (3,017.6 msec). For both tasks, the children scored higher and reacted more quickly under congruent conditions than incongruent conditions. Examining the group differences, the bilingual group performed the congruent tasks more accurately for the Simon Task, whereas their monolingual counterparts performed better under the incongruent conditions of the Stroop Test. Finally, both groups performed equally as well as under the incongruent conditions in the Simon Task and the congruent conditions of the Stroop Test. Looking at the reaction time, the two groups showed little difference under congruent conditions, but the monolingual children carried out the two tasks faster than their bilingual counterparts.



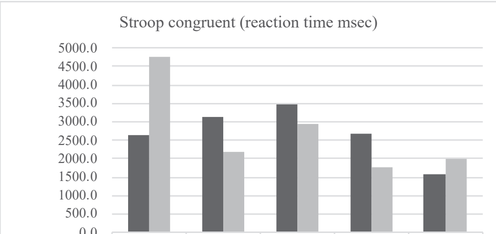
	2-year old	3-year old	4-year old	5-year old	6-year old
monolingual	100.0	100.0	100.0	100.0	100.0
bilingual	100.0	100.0	100.0	100.0	100.0

Figure 5. Stroop congruent (accuracy)



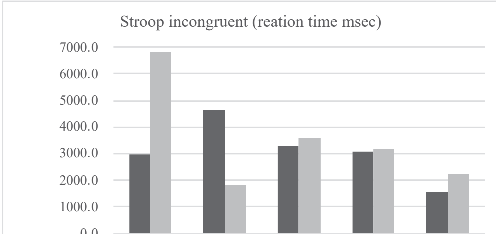
	2-year old	3-year old	4-year old	5-year old	6-year old
monolingual	100.0	85.7	85.7	100.0	100.0
bilingual	57.1	92.9	92.9	85.7	100.0

Figure 6. Stroop incongruent (accuracy)



	2-year old	3-year old	4-year old	5-year old	6-year old
monolingual	2648.0	3119.5	3460.0	2671.0	1589.0
bilingual	4772.7	2184.8	2927.7	1769.7	1991.0

Figure 7. Stroop congruent (reaction time msec)



	2-year old	3-year old	4-year old	5-year old	6-year old
monolingual	2964.0	4637.5	3280.5	3067.5	1593.5
bilingual	6856.0	1804.2	3585.0	3190.4	2240.3

Figure 8. Stroop incongruent (reaction time msec)

Examining the data from the congruent method, a bilingual advantage was evident but only in the accuracy rate of the Simon Task, whereas only small differences were observed between bilingual and monolingual children in the accuracy rate of the Stroop Test as well as in the reaction time of both the Simon Task and Stroop Test. When children's ages were taken into consideration, a bilingual advantage revealed itself only in the two-year old group in terms of accuracy (100% vs 20%) in the Simon Task (Figure 1) and in the reaction time of the three-year olds (1,100 vs 5,186 msec) in the Stroop Test. An age group comparison for each task showed few group differences (Figures 1, 3, 5 & 7) and a monolingual advantage was even detected in the two-year old group reaction time both in the Simon Task (1,089 vs 4911 msec in Figure 3) and the Stroop Test (2,648 vs 4772 msec in Figure 7).

The incongruent tasks showed a monolingual advantage in the accuracy rate of the Stroop Test (94.3% vs 85.7%) but little difference between the two groups for the Simon Task or in the reaction time of both tasks. When an individual age comparison was made, there was an advantage only in the 2-year old bilingual participant in the accuracy rate (100% vs 66.7% in Figure 2) on the Simon Task and the 3-year old group in the reaction time of the Stroop Test (1,804 vs 4,636 msec in Figure 8). Otherwise group differences were minimal except for the monolingual advantage shown in the two-year old group for Stroop accuracy (100 vs 57.1% in Figure 6) and in the reaction time of the Simon Task (3,648 vs 8,356 msec in Figure 4) and Stroop Test (2,964 vs 6,856 msec in Figure 8).

3.2 Brain activation data

The fNIRS or functional Near-Infrared Spectroscopy values (mM-mm), which were collected showing the oxygenated hemoglobin levels, are summarized in Tables 3 to 6 and Figures 9 to 12. In addition to the descriptive data, the results of a series of independent t-tests to compare the bilingual and monolingual children in each age group are shown in Table 5 (Simon Task) and Table 6 (Stroop Test).

When examining the brain activation data for the Simon Task, a bilingual advantage was seen in the 2 and 3-year olds while a monolingual advantage was revealed in the 4 and 5-year olds in the Fp1 (left), whereas in the Fp2 (right) location a bilingual advantage was seen in the 3, 4, and 5-year olds and a monolingual advantage was evident in the 2 and 6-year olds.

In the Stroop Test, a bilingual advantage was seen in the 4 and 5-year olds while a monolingual advantage was revealed in the 6-year olds in the Fp1, whereas an Fp2 bilingual advantage was seen in the 5-year olds alone and a monolingual advantage in the 2, 3, and 4 year old children.

In order to examine any developmental changes in both the bilingual and monolingual groups for the Simon Task in the Fp1 and Fp2 areas the brain, four sets of ANOVA and post-hoc Bonferroni Test were carried out (Figures 13-16). fNIRS data in the bilingual children (Fp1) showed statistical differences among all the age groups ($F(94,166)=4439.6$, $p<.001$, *Eta Squared*=.991), which indicates a gradual increase in brain activation. Fp2 data ($F(4,166)=5824.9$, $p<.001$, *Eta Squared*=.993) showed a U-shaped curve with high activation observed at ages 2 and 6 and lower activation seen at ages 3 to 5. On the other hand, when examining the Fp1 in the monolingual children ($F(4,199)=1316.6$, $p<.001$, *Eta Squared*=.964.) a gradual decrease in brain activation was shown. Their Fp2 fNIRS values ($F(4,199)=2329.9$, $p<.001$, *Eta Squared*=.979) displayed an upside-down U shape with the highest peak at age 4 and lower activation at both ages 2 and 6.

Table 3. Descriptive data on Simon Task

		fNIRS (mM-mm)	*SD*
Fp1Oxy2yr	bilingual	-0.6683	0.88401
	monolingual	1.011	0.62179
Fp2Oxy2yr	bilingual	0.5222	0.69505
	monolingual	0.1972	1.141
Fp1Oxy3yr	bilingual	0.0638	0.25752
	monolingual	0.0051	0.80192
Fp2Oxy3yr	bilingual	0.1547	0.64582
	monolingual	-0.1969	0.39037
Fp1Oxy4yr	bilingual	0.3682	0.22195
	monolingual	1.0381	0.7039
Fp2Oxy4yr	bilingual	-0.1228	0.24068
	monolingual	-0.7887	0.52638
Fp1Oxy5yr	bilingual	-0.2831	0.10969
	monolingual	-0.1173	0.79501
Fp2Oxy5yr	bilingual	-0.3905	0.13989
	monolingual	0.3258	0.51644
Fp1Oxy6yr	bilingual	0.82	0.35386
	monolingual	0.4486	0.17699
Fp2Oxy6yr	bilingual	0.3235	0.60698
	monolingual	0.3567	0.19395

Table 4. Descriptive data on Stroop Test

		fNIRS (mM-mm)	*SD*
Fp1Oxy2yr	bilingual	-0.1796	0.58878
	monolingual	0.9843	1.12073
Fp2Oxy2yr	bilingual	1.0138	0.11258
	monolingual	-0.4044	0.41872
Fp1Oxy3yr	bilingual	-1.1256	0.20835
	monolingual	-0.1857	1.16062
Fp2Oxy3yr	bilingual	-0.5535	0.20013
	monolingual	0.1893	0.57134
Fp1Oxy4yr	bilingual	0.2026	0.18311
	monolingual	0.2024	0.39425
Fp2Oxy4yr	bilingual	-0.0757	0.27526
	monolingual	0.5492	0.33609
Fp1Oxy5yr	bilingual	0.557	0.14819
	monolingual	0.3888	0.31499
Fp2Oxy5yr	bilingual	-0.7803	0.17763
	monolingual	0.1677	0.25481
Fp1Oxy6yr	bilingual	0.4613	0.20247
	monolingual	-1.007	0.06058
Fp2Oxy6yr	bilingual	1.8311	0.19893
	monolingual	-0.8456	0.12132

Identical statistical analyses were carried out on the Stroop Test data, and bilingual children at Fp1 ($F(4,310)=1702.5$, $p<.001$, *Eta Squared*=.956) showed a gradual increase in brain activation. Their Fp2 data ($F(4,310)=619.8$, $p<.001$, *Eta Squared*=.889) displayed a U-shape with higher activation at ages 2 and 6 and lower activation at ages 4 and 5. Meanwhile, monolingual children at Fp1 ($F(4,248)=149.8$, $p<.001$, *Eta Squared*=.707.) underwent a fluctuation of high activation at ages 2 and 4 and low activation at ages 3 and 5. Their Fp2 data ($F(4,248)=356.9$, $p<.001$, *Eta Squared*=.853) showed a U-shape curve with high activation at ages 2 and 6 and low activation at age 4.

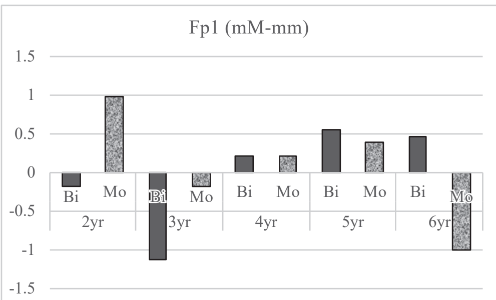


Figure 9. fNIRS data on Fp1 (Simon)

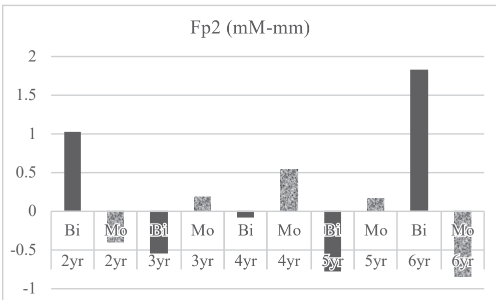


Figure 10. fNIRS data on Fp2 (Simon)2

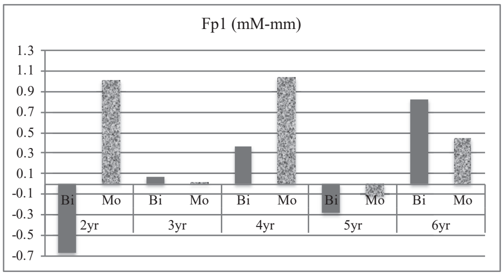


Figure 11. fNIRS data on Fp1 (Stroop)

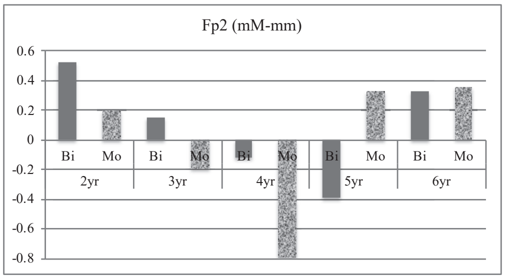


Figure 12. fNIRS data on Fp2 (Stroop)

Table 5. Age comparison (Simon)

	Fp1	Fp2
2 yr	t(371)=-12.202**	t(371)=42.876**
3 yr	t(371)=-10.416**	t(371)=-16.139**
4 yr	t(371)=0.006	t(371)=-10.399**
5 yr	t(371)=6.394**	t(371)=-40.893**
6 yr	t(371)=98.229**	t(371)=159.549**

***p*<. 001

Table 6. Age comparison (Stroop)

	Fp1	Fp2
2yr	t(564)=-25.5,**	t(54)=4.176**
3yr	t(564)=1.2	t(564)=7.6**
4yr	t(564)=-15.9**	t(564)=19.9**
5yr	t(564)=-3.654**	t(564)=-23.535**
6yr	t(565)=15.23**	t*565)=-0.836

***p*<. 001

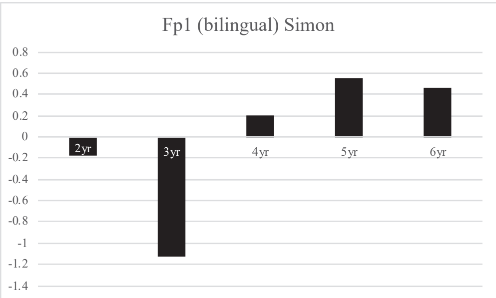


Figure 13. fNIRS in Simon (bilingual Fp1)

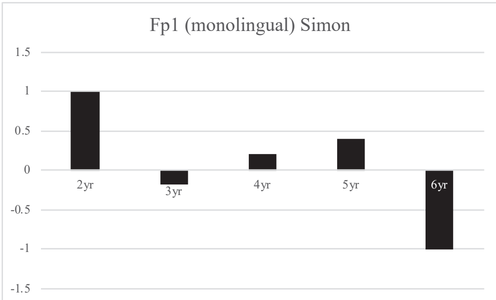


Figure 14. fNIRS in Simon (monolingual Fp1)

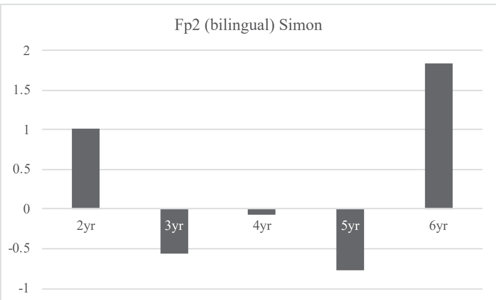


Figure 15. fNIRS in Simon (bilingual Fp2)

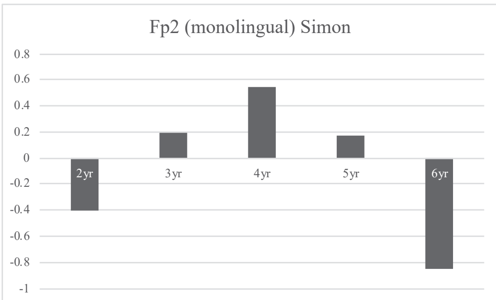


Figure 16. fNIRS in Simon (monolingual Fp2)

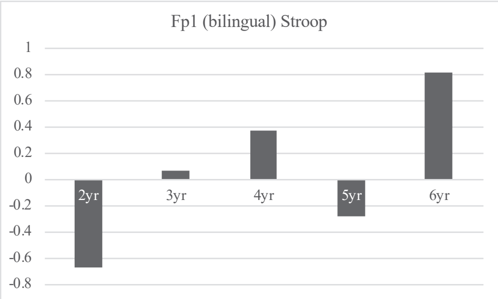


Figure 17. fNIRS in Stroop (bilingual Fp1)

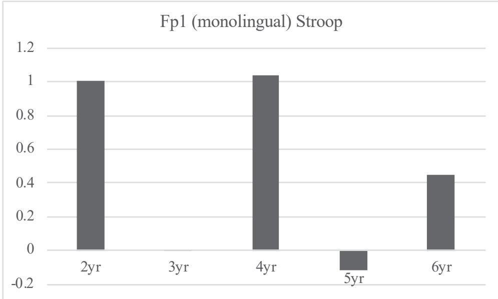


Figure 18. fNIRS in Stroop (monolingual Fp1)

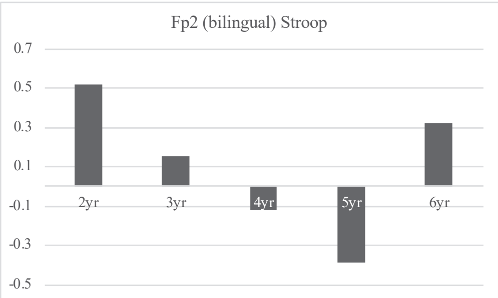


Figure 19. fNIRS in Stroop (bilingual F2)

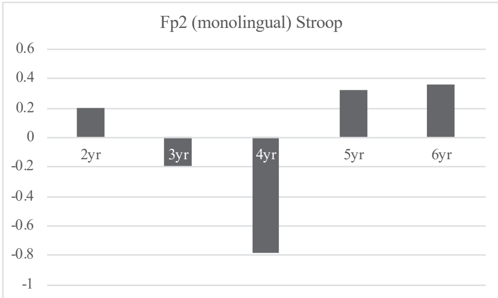


Figure 20. fNIRS in Stroop (monolingual Fp2)

4. Discussion

The behavioural data analysis in section 3.1 proved to be indeterminate as to whether or not there is any bilingual advantage. Considering that the incongruent condition induces more of an inhibitory control than under the congruent condition, an attempt is made here to examine whether or not there was a bilingual advantage when incongruent tasks were given in comparison to congruent tasks. Firstly, the 2-year-old bilingual children, for instance, performed more accurately in both the congruent and incongruent Simon Tasks than the monolingual children (Figures 1 and 2, respectively). This may be interpreted as the children having "no bilingual advantage" because they were already better at performing the congruent task which does not require any inhibitory control. Meanwhile, the same bilingual children performed the Stroop Test with the same rate of accuracy as their monolingual counterparts under congruent conditions (Figure 5) but with more errors under incongruent conditions (Figure 6). This is interpreted as a "monolingual advantage" because the monolingual children had better inhibitory control. Summing this up, a bilingual advantage accounted for only 20% (Simon reaction speed in the 4-year-olds, Simon accuracy in the 5-year-olds, and Stroop accuracy in both the 3 and 4 years olds), a monolingual advantage 30% (Simon accuracy in the 3 and 4 years olds, Stroop speed in the 4 and 5 years olds, and Stroop accuracy 2 and 5 years olds), and no differences seen in 50% of the remaining data.

Secondly, the brain activation data analysis given in section 3.2 was also not straightforward. When the data was re-categorized according to the brain activation area (Fp1 on the left or Fp2 on the right), the fNIRS values (mM-mm) in the Fp1 mostly show a bilingual advantage with a lower activation level for participants up to age 4 in both the Simon Task (not at age 4) and the Stroop Test (up to but not including age 3). In comparison when looking at the Fp2 area for both tasks, a bilingual advantage is only evident at age 5.

Finally, we integrated the behavioural and fNIRS data together to decide which group had an advantage when carrying out an individual incongruent task by comparing the task performance speed, accuracy, and fNIRS values. The task speed, for instance, needed for the 2-year old bilingual children to perform the Simon incongruent task was significantly faster than that of their monolingual counterparts (Figure 4), but the fNIRS values (brain activation level) at Fp1 in the bilingual children were significantly less than the monolingual children (Figure 9), which is interpreted as a bilingual advantage. A monolingual advantage was observed when the 5-year-old group showed significantly less brain activation in the Fp1 region than seen in their bilingual counterparts (Figure 9), though their task performance speeds showed no differences on the Simon Task (Figure 3). Meanwhile, no group advantage was detected when the 3-year-old bilingual group carried out the incongruent Simon task significantly less accurately (Figure 2) even though their brain activation level was significantly less than their monolingual counterparts. This procedure was repeated for every group, the results listed here: (1) With regard to the two brain regions of Fp1 and Fp2, 8 bilingual vs 6 monolingual advantage in the Fp1 while 4 bilingual vs 9 monolingual advantage in the Fp2, and (2) with regard to age comparison, 3 bilingual vs 4 monolingual advantage at age 2, 3 bilingual vs 1 monolingual advantage at age 3, 3 bilingual vs 1 monolingual advantage at age 4, 3 bilingual vs 0 monolingual advantage at age 5, 0 bilingual vs 6 monolingual advantage at age 6.

Thus, the bilingual advantages in performing incongruent tasks are very limited to only the brain region in Fp1 in the age groups of 3, 4, and 5 years olds. However, this indeterminate finding could be significant in that our participants are bilinguals of two linguistically distant languages - alphabetical English and logographic Japanese.

The rigorous selection of the participants in this study left us with only 18 out of the original 28 children. The inclusion of many more children in each age bracket is necessary in the future to validate our tentative conclusion in this study.

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