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Graded bilingual effects on attentional network function in Chinese high school students

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Abstract

Effective communication in multilingual environments requires bilinguals to constantly monitor linguistic cues. It is hypothesized that the constant need to monitor may result in improved attention. However, previous investigations have reported mixed, often null results, with positive findings attributed to non-linguistic variables. To address these issues, we investigated whether higher levels of bilingualism were associated with improved attentional function in a sample of culturally and socioeconomically homogenous Mandarin–English speaking bilingual adolescents. Participants completed the Attention Network Task to assess attentional network function. Data were analyzed using linear mixed-effects models in order to account for nontrivial differences. Mixed results provide partial support for domain general cognitive benefits associated with higher levels of bilingualism. Both improved and reduced performance differed based on the specific dimension of bilingualism and the attentional network assessed. Findings support the conclusion that separable dimensions of bilingual language experience assert different influences on attentional network function.

Introduction

Bilinguals' remarkable ability to successfully function across a range of diverse linguistic environments is a source of considerable investigation and controversy (Antoniou, 2019). The main source of this controversy stems from reports of improved performance by bilinguals relative to monolinguals on non-linguistic tasks measuring different dimensions of executive function, a multi-dimensional mental construct consisting of multiple dissociable functions that regulate cognition (Miyake, Friedman, Emerson, Witzki, Howerter & Wager, 2000). Evidence supporting bilingual effects on executive function has been reported in studies administering a number of different tasks to samples across a wide age range (Ware, Kirkovski & Lum, 2020). While considerable evidence supports non-linguistic benefits of bilingualism in adult samples (Ware et al., 2020), results in young people, defined by the World Health Organization (WHO) as those between 10-24 years of age, are more mixed (Giovannoli, Martella, Federico, Pirchio & Casagrande, 2020; Lowe, Cho, Goldsmith & Morton, 2021).

Because both of a bilinguals' languages are thought to be simultaneously active (Abutalebi & Green, 2007; Costa, Roelstraete & Hartsuiker, 2006; Hermans, Bongaerts, De Bot & Schreuder, 1998; Kroll, Dussias, Bogulski & Kroff, 2012), and because intrusion errors among bilinguals are rare (Gollan & Ferreira, 2009), some underlying inhibitory control network must be recruited in support of successful communication (Green, 1998). Consequently, most of the published studies on bilingual effects in young people investigate differences in inhibition, sometimes referred to as inhibitory control (Giovannoli et al., 2020; Privitera & Weekes, 2022; Ware et al., 2020). Furthermore, the ADAPTIVE CONTROL HYPOTHESIS posits that the demands placed on this inhibitory control network differ depending on whether interaction occurs in a single language, dual language, or dense code-switching context (Green & Abutalebi, 2013). Despite these theoretically-grounded hypotheses, published results are mixed (Gunnerud, Ten Braak, Reikerås, Donolato & Melby-Lervåg, 2020; Lehtonen, Soveri, Laine, Järvenpää, De Bruin & Antfolk, 2018; Lowe et al., 2021; Paap, 2019; Paap, Mason & Anders-Jefferson, 2021; Paap & Sawi, 2014), with the most consistently reported finding, improved performance across all trial conditions (i.e., improved monitoring), supporting a bilingual effect that is not specific to inhibition (Bialystok & Craik, 2022; Hilchey & Klein, 2011; cf. Hilchey, Saint-Aubin & Klein, 2015).

Evidence supporting positive influences of bilingualism suggests that experience using a second language may confer non-linguistic benefits that are broader, possibly manifesting as differences in attention, which subserves other dimensions of executive function (Bialystok & Craik, 2022; Braver, 2012; Friedman & Miyake, 2017). A bilingual effect on attention is in alignment with domain general benefits, possibly resulting as a consequence of the need for bilinguals to constantly monitor diverse linguistic environments in order to identify which language to inhibit and which to use (Costa, Hernández & Sebastián-Gallés, 2008). This need to monitor may modulate "bilingual language control" networks (Calabria, Costa, Green & Abutalebi, 2018), which include the anterior cingulate cortex, a structure involved in attentional control (Petersen & Posner, 2012; Posner & Petersen, 1990). These effects also align with a more recent proposal from observations of infants that exposure to a bilingual home may necessitate more frequent sampling of environmental stimuli, and that this may relate to reported attentional effects in bilingual infants (D'Souza & D'Souza, 2021).

Attention, like executive function, is thought to consist of multiple, independent but related abilities including alerting, orienting, and executive control (Petersen & Posner, 2012; Posner & Petersen, 1990). Each of these abilities is thought to be subserved by a separate network of brain structures (Fan, McCandliss, Fossella, Flombaum & Posner, 2005), overlapping with structures previously identified to be influenced by bilingual experience (Tao, Wang, Zhu & Cai, 2021). Studies assessing differences in the function of attentional networks typically administer the Attention Network Task (ANT; Fan, McCandliss, Sommer, Raz & Posner, 2002). The ANT, a combination of a Flanker task (Eriksen & Eriksen, 1974) and a cueing task (Posner, 1980), allows for assessment of these three independent and neurologically distinct attentional networks (Fan et al., 2002, 2005; Posner, 2016; Posner & Fan, 2008). The ALERTING NETWORK underlies the ability to activate and sustain a heightened level of arousal. Experimentally, this is elicited through the presentation of a cue that provides temporal but not spatial information about a target stimulus. The presentation of an alerting cue generally results in faster responses. Allocating attention to one of many possible locations based on incoming sensory information received from our environment relies on the ORIENTING NETWORK. Tasks that measure differences in orienting rely on the use of spatially informative cues that provide accurate information about target stimuli, generally reducing response times. Finally, the EXECUTIVE CONTROL NETWORK underlies the ability to monitor stimuli and resolve conflict. On the ANT, conflict takes the form of incongruent trials (i.e., → → ← → →) presented among congruent trials (i.e., → → → → →). Responses are generally slower on incongruent relative to congruent trials.

Among studies using the ANT to investigate the impact of bilingualism, improved monitoring and/or executive control network efficiency in bilinguals is commonly reported (Costa, Hernández, Costa-Faidella & Sebastián-Gallés, 2009; Costa et al., 2008; Novitskiy, Shtyrov & Myachykov, 2019; Pelham & Abrams, 2014; Sabourin & Vīnerte, 2019; Tao, Marzecová, Taft, Asanowicz & Wodniecka, 2011; Woumans, Ceuleers, Van der Linden, Szmalec & Duyck, 2015; Yang & Yang, 2016). To date, fewer studies have identified bilingual effects on alerting and orienting network function (Arora & Klein, 2020). In one seminal study (Costa et al., 2008), increased alerting network efficiency in bilinguals was thought to support monitoring and conflict resolution processes. While consistent with domain general benefits, this interpretation conflicts with other reports of improved monitoring independent of increased alerting network efficiency (Tao et al., 2011; Yang & Yang, 2016). Bilingual effects on orienting are more complex to interpret, and may be influenced by a participant's linguistic environment. In their interpretation of a significant bilingual effect on orienting, Woumans and colleagues (2015) pointed to linguistic environment differences to explain their result in light of a previous null report (Costa et al., 2008). By their logic, bilinguals are potentially less reliant on contextual cues to determine which language to use if they live in an environment where most people can speak both possible languages (e.g., Catalonia). Accordingly, larger orienting effects associated with bilingualism would be less likely to be observed in samples drawn from these environments.

Recently, investigations of bilingual effects on executive function, including attentional network function, have shifted focus from exclusive comparisons of bilingual and monolingual samples to differences in bilingual language experience within or between samples of bilinguals (DeLuca, Rothman, Bialystok & Pliatsikas, 2019, 2020). These studies generally focus on differences in language proficiency (i.e., how well you can use a language), dominance (i.e., how much you use a language), and immersion (i.e., how much you are exposed to a language), domains which are also assessed by popular self-report measures of language experience (e.g., Li, Zhang, Yu & Zhao, 2020; Marian, Blumenfeld & Kaushanskaya, 2007). Higher levels of second language proficiency have been associated with improved inhibition on the ANT (Novitskiy et al., 2019), and monitoring on a Flanker task (Privitera, Momenian & Weekes, 2022; Xie, 2018; Xie & Pisano, 2019). Improved inhibition has also been reported on the Stroop task in bilinguals who are more balanced in both proficiency and language dominance (Yow & Li, 2015). Additionally, higher levels of second language immersion, operationalized as an earlier age of acquisition, have been associated with improved monitoring on the Lateralized ANT (Tao et al., 2011), and Simon task (Champoux-Larsson & Dylman, 2021), while other experiences, such as second language immersion in school, have been associated with improved inhibition and attention after as little as one year (Chamorro & Janke, 2020). Findings from these studies highlight the value of exploring how differences in the degree of bilingualism can impact on executive and attentional function, following a recent trend toward operationalizing bilingualism as a multi-dimensional continuum (De Bruin, 2019; Gullifer, Kousaie, Gilbert, Grant, Giroud, Coulter, Klein, Baum, Phillips & Titone, 2021; Kremin & Byers-Heinlein, 2020; Luk & Bialystok, 2013).

While a number of studies have used the ANT to explore the impact of bilingualism on attentional network function (Arora & Klein, 2020), few of these studies have been conducted in adolescent samples. Presently, whether bilingualism influences attentional network function in adolescents remains an underexplored and open question. One explanation for this limited inquiry may relate to the complexities associated with studying attention during a period in which development reliably influences task performance, complicating the interpretation of results (Giovannoli, Martella & Casagrande, 2021). Alternatively, it may result from the expectation that, since late adolescence is a period approaching a developmental peak in executive functioning (Anderson, 2002), bilingual effects would be difficult to identify due to a ceiling effect on task performance (Bialystok, 2016; cf. Paap, Wagner, Johnson, Bockelman, Cushing & Sawi, 2014).

The present study aimed to explore bilingual effects on attentional network function within a sample of bilingual Mandarin–English speaking adolescents living in Mainland China. Using an online version of the original ANT (Fan et al., 2002), we investigated whether differences in the *degree* of bilingualism were associated with differences in overall monitoring, and the function of the alerting, orienting, and executive control networks. Given the paucity of research investigating bilingual effects on attention in this age group, and inconsistent previous findings,

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we limit our *a priori* predictions to those that have been most widely reported. We expect to observe a positive association between degree of bilingualism and monitoring, consistent with domain general cognitive benefits of bilingualism (Bialystok & Craik, 2022). Additionally, we expect to observe a positive association between degree of bilingualism and executive control (Arora & Klein, 2020). Considering that the majority of past studies compare monolingual with bilingual samples and that bilingual language status is generally assessed through proficiency (Surrain & Luk, 2017), we expect that improved monitoring and executive control would be associated with higher levels of proficiency. For these reasons, our investigation of bilingual effects on the alerting and orienting networks should be considered exploratory.

Methods

Participants

A sample of Mandarin–English bilingual participants ($n = 41$, 31 females; $M_{age} = 16.26$ years, $SD_{age} = 1.57$ years) was recruited from a highly-selective international boarding school in Shenzhen, China. Participants were all native Mandarin speakers (L1) attending school full time where English (L2) was the language of instruction and assessment. Participants were awarded community service hours toward school graduation requirements. Written informed consent was collected from all participants. For participants below the age of 18, informed consent was granted by parents or legal guardians. Approval for this study was granted by the Human Research Ethics Committee of the University of Hong Kong (#EA200010).

Questionnaires and task

Language history

Language history data were collected via the English language version of the Language History Questionnaire (LHQ-3; Li et al., 2020). This self-report instrument measures language experience across multiple dimensions and for any languages a participant uses. In order to more easily compare our results with the wider literature on bilingual effects, analyses only included aggregate scores for L1 and L2 proficiency, immersion, dominance, and the ratio of dominance between L2 and L1 (L2/L1 dominance ratio). Participants were asked additional questions about the number of other languages they used, how often they switched languages (scale from 1-7), the number of hours they spent playing video games or musical instruments each week, and parental education level as an index of SES. Finally, to control for potential modulatory effects of stress on executive function (Plieger & Reuter, 2020), participants completed the 10-item version of the Perceived Stress Scale (PSS-10; Cohen, 1988).

Attention Network Task

An online version of the ANT (Fan et al., 2002) was administered to all participants using the Gorilla online experiment builder (Anwyl-Irvine, Massonnié, Flitton, Kirkham & Evershed, 2020). The ANT consisted of three phases administered in the following order: (1) no-cue practice (2) cued practice; and (3) testing phase containing both no-cue and cued trials. Before the practice trials commenced, participants were given written instructions, telling them to place their left index finger on the Q key and their right index finger on the P key of their computer keyboard and to focus on the fixation cross during the whole task (i.e., not to move their eyes to the target). A reminder of the stimulus-response mapping remained visible at the top of the screen during each of the two practice phases.

Task conditions for the ANT were identical to those described in the original paper (Fan et al., 2002). In total, 24 practice trials were completed (12 no-cue, 12 cued), which included examples of each of the possible trial types based on item congruency (congruent, incongruent, neutral) and cue condition (no cue, center cue, double cue, spatial cue). Feedback was provided after each practice trial in the form of a checkmark (correct) or crossmark (incorrect) presented directly below the fixation cross after a response was registered. The testing phase consisted of 3 blocks each containing 96 trials for a total of 288 trials. Testing blocks each contained equal numbers of congruent, incongruent, and neutral trials, as well as the 4 cue conditions, and the presentation of task stimuli either above or below the fixation cross. No feedback was provided during trials administered in each of the 3 testing blocks. Trial presentation in both the practice and experimental phases was randomized.

Online data collection

We used the Gorilla online experiment builder (Anwyl-Irvine et al., 2020) for task creation and data collection. Participants were sent a private link through email that directed them to the task administration website. Participants were first screened based on the device they used to access the online task, with tablet and smartphone logins automatically rejected from continuing. This ensured that all participants completed tasks on either a desktop or laptop computer. Participants were instructed in English to complete the behavioral tasks in an environment that was free from possible distractions, and to not split their attention by using their phone or opening additional websites. Additionally, participants were asked to complete the whole test battery in one session with minimal interruptions. Short breaks between each phase of the study were included to reduce the likelihood that participants would experience fatigue or boredom. Similar instructions were provided before each task.

After accessing the task administration site, participants gave informed consent, completed the LHQ-3 with other self-reported background measures, and then completed two behavioral tasks as part of a larger study (order counterbalanced; only ANT task data described in this manuscript). Finally, participants completed the PSS-10. After all phases were completed, participants were given additional information about the research study including a summary of the main objectives. Participants were only included if they completed all phases of the study in a single session (e.g., no evidence of extended stopping). Participants who began the study but had not completed all phases were rejected before data were reviewed. In the event a participant began the study but did not progress past the informed consent stage, they were sent another email asking them to begin the study over again with an additional reminder that all phases of the study had to be completed in a single session.

Data analysis

Linear mixed-effects modeling (LMEM) was used to analyze reaction time (RT) data via the lmer function from the lme4 package

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Table 1: Demographic and language history data

	M	SD	Range
Age (years)	16.26	1.57	13 - 19
Socioeconomic status (1-4 points)	2.40	0.70	1 - 4
PSS-10 score (0-40 points)	18.97	5.66	10 - 32
Weekly video game time (hours)	10.19	12.85	0 - 70
Weekly musical instrument time (hours)	1.47	2.22	0 - 9
Number of languages used	2.38	0.58	2 - 4
Frequency of language switching (1-7 points)	4.70	1.75	1 - 7
L2 experience (years)	10.49	2.06	5 - 15
L1 proficiency (0-1 point)	0.89	0.10	0.57 - 1
L1 dominance (0-1 point)	0.56	0.11	0.4 - 0.94
L2 immersion (0-1 point)	0.64	0.10	0.39 - 0.82
L2 proficiency (0-1 point)	0.72	0.12	0.5 - 1
L2 dominance (0-1 point)	0.43	0.08	0.28 - 0.59
L2/L1 dominance ratio	0.79	0.15	0.46 - 1.23

(Version 1.1-26; Bates, Mächler, Bolker & Walker, 2015) in R (Version 4.0.3; R Core Team, 2021). The nlminb optimizer from the optimx package was used during each stage of model fitting. Only incorrect trials, trials with RTs shorter than 150 ms, or trials with extremely long RTs thought to result from Internet connectivity issues (e.g., 10000 ms) were removed prior to analysis. Data were not further trimmed in order to provide the conditions under which a bilingual effect on task performance could more readily be identified (Zhou & Krott, 2016). The total number of participants [$n = 41$] and trials [11,053] included in the analysis were within recommended norms for LMEM (Brysbaert & Stevens, 2018). RT data were non-normally distributed, and were log transformed prior to modeling. All categorical variables were sum coded, and all continuous independent variables were standardized (i.e., z-score).

We used variance inflation factor (VIF) as a measure of collinearity between variables of interest. Variables with a VIF greater than 5 were evaluated individually before inclusion in model fitting (Craney & Surles, 2002). The model fixed-effects structure included cue condition, item congruency, L1 dominance, L1 proficiency, L2 dominance, L2 proficiency, L2 immersion, L2/L1 dominance ratio, SES, hours per week playing video games, hours per week playing musical instruments, and language switching frequency. Interactions between cue condition and item congruency, as well as separate two-way interactions between cue condition, item congruency, and all other variables of interest, were also included. Finally, gender, task block, task order, age, reported stress score, and number of languages spoken were included as control variables. All main effects and interaction terms were included based on the *a priori* expectation that both linguistic and non-linguistic variables would influence the emergence of a bilingual effect (Bialystok, 2006; Costa et al., 2008; D'Souza, Moradzadeh & Wiseheart, 2018; Gathercole, Thomas, Jones, Guasch, Young & Hughes, 2010; Naeem, Filippi, Periche-Tomas, Papageorgiou & Bright, 2018; Schroeder, Marian, Shook & Bartolotti, 2016). The inclusion of age as a control variable is especially crucial, considering documented maturational differences in the development of the separate attentional networks (Boen, Ferschmann, Vijayakumar, Overbye, Fjell, Espeseth & Tamnes, 2021).

In order to assess for bilingual effects on the function of the three attentional networks (i.e., alerting, orienting, and executive control), the categorical variables cue condition and item congruency were dummy coded, with one level of each factor set as a reference level. Appropriate reference levels for comparison were set based on guidance outlined in previous reports (Fan et al., 2002). During the assessment of alerting and orienting network function, the variable item congruency was sum coded, allowing estimates to be compared to the grand mean across item congruency conditions. The function of the alerting network was assessed by calculating the difference between the no cue and double cue conditions (Fan et al., 2002). With the no cue condition set as the reference level, a bilingual effect on alerting would present as a significant interaction between any bilingual experience variable and the double cue condition with a negative coefficient (Costa et al., 2008; Fan et al., 2002).

Orienting network efficiency was calculated based on the difference between the center cue (temporally informative but spatially irrelevant) and spatial cue conditions. With the center cue condition set as the reference level, a bilingual effect on orienting would present as a significant interaction between any bilingual experience variable and the spatial cue condition with a negative coefficient.

Finally, executive control network function was measured by first sum coding the cue condition variable to allow for the average of each congruency condition to be compared to the grand mean across cue conditions, and then dummy coding item congruency with the congruent condition set as the reference level. Under these conditions, a significant interaction between any bilingual experience variable and the incongruent condition with a negative coefficient would support the presence of a bilingual effect on executive control.

Fitting our model's random effects structure began with a maximal model (Barr, Levy, Scheepers & Tily, 2013) which included random intercepts for participants and by-participant random slopes for cue condition and item congruency. Random effects correlation parameters were not included during model fitting. Random effects structure reduction followed procedures outlined in our previous work (Momenian, Bakhtiar, Chan, Cheung & Weekes, 2021) and was based on principal component analysis (PCA) to measure the variance accounted for by each of the random effects, and model comparison using likelihood ratio tests (LRT). Random effects were removed only if the resultant model was not significantly different from a model that included it. LRTs were also used to compare the most parsimonious random effects structure with an identical model that included random effects correlation parameters. Correlation parameters were only included in the final model if their inclusion resulted in a significant difference from a model in which they were not included. Finally, to address non-normal residual distribution, absolute standardised residuals exceeding 2.5 standard deviations were removed (Baayen & Milin, 2010).

Due to high levels of accuracy (> 93%) across all cue and item congruency conditions on the ANT, we were unable to validly analyze accuracy data.

Results

Participant characteristics

On average, participants had over 10 years of English language experience ($M = 10.49$, $SD = 2.06$). Participants reported using Cantonese ($n = 5$), Spanish ($n = 4$), French ($n = 2$), and Japanese ($n = 1$) in addition to Mandarin and English. Additional demographic and language history data are summarized in Table 1. While all participants unsurprisingly reported higher levels of proficiency in their L1, the range of reported proficiency scores for L1 and L2 were very similar, perhaps as a consequence of the educational linguistic environment. Correlations between LHQ-3 lingusitic aggregate scores are presented in Supplementary Materials.

Task performance and modeling

Removal of incorrect trials ($n = 353$), trials with RTs < 150 ms ($n = 20$), and trials with long reaction times due to suspected Internet connectivity issues (> 10000 ms; $n = 2$) resulted in the inclusion of 11053 trials from 41 participants for analysis (3.28% of data removed). Post-trimming performance data from the ANT are summarized in Table 2. Average RT (Table 2A) and error rates (Table 2B) are presented for each congruency and cue condition separately. Differences in RT and accuracy between trials containing left and right pointing arrow stimuli and above and below spatial cues were not significant ($ps > .20$). For this reason, data were combined.

Initially, high multicollinearity was identified between L2 dominance (VIF = 34.92), L2/L1 dominance ratio (VIF = 24.55), and L1 dominance (VIF = 17.46). After removing L2 dominance, VIF values were greatly decreased for L2/L1 dominance ratio (VIF = 7.22) and L1 dominance (VIF = 6.69). The decision was made to include both variables given our *a priori* motivation to best capture the heterogeneity of bilingual experiences in our model. Finally, the trimming of extreme residuals prior to final model fitting resulted in the removal of 229 data points (1.91% of data removed) and a significantly improved final model fit (ΔAIC = -4,635.7; ΔBIC = -4,637.3).

Attentional network function results are summarized in Table 3. Models containing random by-participant slopes for both cue condition and item congruency would not converge. Additionally, the inclusion of by-participant random slopes for either cue condition or item congruency resulted in a singular fit. Due to these issues, our final model contained only random intercepts for participants and no correlation parameters in the random effects structure. Full results for each model can be accessed on Open Science Framework (https://doi.org/10.17605/OSF.IO/PJVRK). Corresponding figures for each model are presented in Supplementary Materials.

Main effects

Significant main effects of reported L2 proficiency and the number of languages used were found, with higher reported levels of both variables associated with faster RTs on all trial types. In contrast, higher reported levels of L2/L1 dominance ratio were significantly associated with slower RTs across all trial types.

Alerting Network Function

A significant interaction with the double cue condition was identified for reported L2 immersion and language switching frequency. Higher reported levels of each bilingual experience variable were associated with slower RTs on double cue trials relative to no cue trials, indicating a significantly decreased alerting effect.

Orienting Network Function

A significant interaction was identified between L2 proficiency and the spatial cue condition, with higher reported levels of L2 proficiency associated with slower RTs on spatial cue trials relative to center cue trials, supporting a decreased orienting effect. Additionally, significant interactions between L2/L1 dominance ratio and the spatial cue condition were found, with higher levels of L2/L1 dominance ratio associated with faster RTs on spatial cue trials relative to center cue trials, indicating an increased orienting effect.

Executive Control Network function

The presence of a significant interaction between cue and congruency necessitated the building of separate models in order to assess the influence of bilingual experience on executive control network function. In total, four separate executive control models were fit using the same fixed and random effects structure of the full model. No significant relationship between any bilingual experience variable and incongruent trial condition was identified in the no cue model (Table 4). Results for separate cue condition models are presented in Supplementary Materials. A single interaction between L2 immersion and incongruent trial condition was identified in both the center cue and double cue models. The direction of this relationship differed for each model – with higher levels of L2 immersion associated with reduced executive control in the center cue model, but improved executive control in the double cue model. Finally, improved executive control associated with higher levels of L2 proficiency was identified in the spatial cue model. Additionally, this model identified significantly reduced executive control associated with higher levels of L2 immersion and a marginally significant reduction associated with L2/L1 dominance ratio.

Discussion

Using a sample of bilingual Mandarin–English-speaking adolescents, the present study identified partial evidence in support of bilingual effects on attentional network function associated with separate dimensions of bilingual experience. We report: 1) global reductions in RT associated with higher reported levels of L2 proficiency and number of languages used; 2) increased orienting effects associated with higher reported L2/L1 dominance ratio; 3) improved executive control on spatial cue trials associated with higher reported L2 proficiency; and, 4) improved executive control on double cue trials associated with higher reported L2 immersion. However, we also identified: 1) a global increase in RT associated with higher reported levels of L2/L1 dominance ratio; 2) decreased alerting effects associated with higher levels of L2 immersion and language switching frequency; 3) decreased orienting effects associated with higher levels of L2 proficiency and L2/L1 dominance ratio; and, 4) reduced executive control on center cue and spatial cue trials associated with higher reported L2 immersion. These results highlight the complexities associated with investigating the influence of bilingual language experience on executive function, and underscore the importance of collecting detailed, multidimensional measures of language experience (e.g., Gullifer et al., 2021; Sulpizio, Del Maschio, Del Mauro, Fedeli & Abutalebi, 2020).

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Table 2: Mean RT and error rates under each condition

Congruency	Cue Condition: None	Center	Double	Spatial
(A) Mean RTs (ms) and standard deviations:				
Congruent	485 (79)	495 (84)	430 (72)	466 (82)
Incongruent	521 (68)	435 (70)	484 (81)	417 (68)
Neutral	486 (71)	438 (71)	438 (72)	422 (71)
(B) Error rate (%) and standard deviations:				
Congruent	0.01 (0.03)	0.07 (0.07)	0.01 (0.02)	0.06 (0.08)
Incongruent	0.04 (0.05)	0.02 (0.03)	0.04 (0.06)	0.01 (0.03)
Neutral	0.02 (0.03)	0.02 (0.04)	0.02 (0.04)	0.02 (0.04)

Table 3: Summary of ANT effects and interactions of interest

Fixed effects				
Main effects	*t* value	Std. error	*p* value	95% CI
Intercept	546.26	0.005	< 0.001	2.653, 2.672
Age	−0.64	0.005	0.528	−0.014, 0.007
L2 proficiency	−2.59	0.009	0.013	−0.041, −0.006
L2 immersion	1.10	0.005	0.278	−0.004, 0.014
L2/L1 dominance ratio	2.28	0.011	0.028	0.003, 0.046
Switching frequency	1.19	0.005	0.243	−0.004, 0.016
Number of languages used	−2.39	0.005	0.022	−0.022, −0.002
Alerting (No Cue Ref.)	*t* value	Std. error	*p* value	95% CI
L2 proficiency X Double cue	−0.57	0.003	0.568	−0.009, 0.005
L2 immersion X Double cue	4.22	0.002	< 0.001	0.004, 0.011
L2/L1 dominance ratio X Double cue	−1.19	0.004	0.236	−0.012, 0.003
Switching frequency X Double cue	2.01	0.002	0.044	0.000, 0.008
Orienting (Center Cue Ref.)	*t* value	Std. error	*p* value	95% CI
L2 proficiency X Spatial cue	4.43	0.004	< 0.001	0.009, 0.022
L2 immersion X Spatial cue	0.39	0.002	0.700	−0.003, 0.004
L2/L1 dominance ratio X Spatial cue	−2.99	0.004	0.003	−0.019, −0.004
Switching frequency X Spatial cue	−0.20	0.002	0.840	−0.004, 0.003
Executive Control (Congruent Ref.)	*t* value	Std. error	*p* value	95% CI
Incongruent condition	−3.58	0.001	< 0.001	−0.008, −0.002
L2 proficiency X Incongruent	−0.05	0.003	0.960	−0.006, 0.006
L2 immersion X Incongruent	1.32	0.002	0.187	−0.001, 0.005
L2/L1 dominance ratio X Incongruent	0.79	0.003	0.431	−0.004, 0.009
Switching frequency X Incongruent	−0.80	0.001	0.425	−0.005, 0.002
Random effects	*Variance*	*SD*		
Subject (intercept)	0.001	0.026		
Residual	0.004	0.060		

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Table 4: Summary of executive control results: No cue model

Fixed effects	*t* value	Std. error	*p* value	95% CI
Intercept	534.51	0.005	< 0.001	2.688, 2.708
Incongruent condition	10.41	0.003	< 0.001	0.024, 0.035
L2 proficiency X Incongruent	0.75	0.006	0.454	−0.007, 0.017
L2 immersion X Incongruent	0.52	0.003	0.606	−0.005, 0.008
L2/L1 dominance ratio X Incongruent	−0.03	0.007	0.974	−0.013, 0.013
Switching frequency X Incongruent	−0.62	0.003	0.536	−0.009, 0.005
Random effects	*Variance*	*SD*		
Subject (intercept)	0.001	0.026		
Residual	0.004	0.061		

Previous studies investigating bilingual effects on attention using the ANT have reported mixed findings. In their Bayesian meta-analysis, Arora and Klein (2020) identified credible evidence in support of reduced interference effects in young adult bilinguals, but no evidence for this outcome in children. Additionally, there was no credible evidence in support of bilinguals demonstrating a global reduction in RT across all trial types, nor increased efficiency in either alerting or orienting. These findings conflict with those reported in the present study, but must be considered in light of relevant methodological differences. The pattern of results reported in Arora and Klein (2020) emerged from comparisons between monolingual and bilingual samples with no distinctions made between separate dimensions of bilingual experience. Additionally, although likely unavoidable given the small number of studies conducted in high-school-age bilinguals, the majority of included studies investigated bilingual effects in samples that were either considerably younger or older than the sample reported in the present study. Variability in age across samples from previous studies is significant given differences in the development of the separate attentional networks. In a recent mixed cross-sectional and longitudinal study, Boen and colleagues (2021) administered the ANT to a diverse developmental sample spanning from late childhood to young adulthood. While executive control stabilized toward the end of adolescence, both orienting and altering networks were not mature, continuing to develop into young adulthood. For this reason, the findings of the present study will be considered in light of findings from studies that are more directly comparable.

Improved monitoring associated with higher English proficiency and multilingualism

We report evidence in support of improved monitoring (i.e., global reduction in RT) associated with higher reported levels of L2 proficiency. A similar finding, associated with bilingualism compared to monolingualism, was initially reported on the ANT by Costa and colleagues (2008), and further reported by more task-inclusive empirical (Hilchey & Klein, 2011; cf. Hilchey et al., 2015) and theoretical syntheses (Bialystok & Craik, 2022). Task conditions are thought to influence the emergence of this effect with more balanced ratios of congruent and incongruent trials, such as in the present study, facilitating the identification of differences in monitoring (Costa et al., 2009). Despite the over-reliance on comparisons between monolingual and bilingual samples in the extant literature, there is at least some evidence supporting a relationship between L2 proficiency and improved monitoring. Global decreases in RT have been reported in early bilinguals compared to less proficient late bilinguals on the ANT (Tao et al., 2011), as well as within samples of bilinguals who differ in their degree of L2 proficiency, with higher proficiency associated with faster RTs on all trial types on a Flanker task (Xie, 2018; Xie & Pisano, 2019; Xie & Zhou, 2020). While we also report improved monitoring associated with higher reported number of languages used, we are cautious regarding the significance placed on this finding – considering that measures of multilingualism were limited in scope.

Increased orienting associated with higher English use relative to Mandarin

Bilingual effects on alerting and orienting have been inconsistently reported in young people (Arora & Klein, 2020), possibly due to the instability of these networks at this point in development (Boen et al., 2021). Reported alerting effects are typically null (Antón, Duñabeitia, Estévez, Hernández, Castillo, Fuentes, Davidson & Carreiras, 2014; Arredondo, Hu, Satterfield & Kovelman, 2017; Tao et al., 2011; Yang & Yang, 2016), with only one previous study reporting a significant bilingual effect (Costa et al., 2008). Significant bilingual effects on orienting network function are similarly rare (Woumans et al., 2015; Yang & Yang, 2016), with null results reported fairly consistently (Arredondo et al., 2017; Costa et al., 2008; Tao et al., 2011). Our reported bilingual effect on orienting network function associated with higher reported levels of L2/L1 dominance ratio is consistent with some of these previous reports, but merits further discussion with respect to the characteristics of our sample. Because this finding was specific to L2/L1 dominance ratio, and because the opposite relationship was reported with L2 proficiency, we interpret it as increased sensitivity to environmental cues in support of identifying the appropriate target language in bilinguals who are using their L2 more due to higher levels of foreign language motivation. Put another way, these students might be sensitive to identifying opportunities in which to use their L2 in order to develop their proficiency, but those who perceive themselves as being sufficiently proficient are perhaps less motivated and, as a result, less sensitive to these cues. It should be noted that, while L2/L1 dominance ratio and L2 proficiency were positively correlated, we did not assess differences in the motivation to use English, and our interpretation should be considered speculative.

While our interpretation may be considered unusual if our sample was drawn from the general population, it may represent the tuning of cognitive control as a consequence of native Mandarin speaking students having extended experience in a highly-competitive, immersive English language boarding school environment. For this reason, it is consistent with the ADAPTIVE CONTROL HYPOTHESIS as it illustrates an example of how the language control pressures of a unique interactional context can

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impact on general cognitive processes (Green & Abutalebi, 2013). Specifically, in the case of our sample, the pressures associated with being taught and assessed exclusively in English might tune the orienting network to be more sensitive to cues. However, perceiving oneself as being sufficiently proficient in English may reduce that sensitivity. It is also consistent with previous interpretations of significant bilingual effects on orienting that are specific to a linguistic context. When interpreting a significant increase in orienting associated with bilingualism that conflicted with a previous null report, Woumans and colleagues (2015) emphasized the importance of considering the linguistic environment of a studied population. Specifically, they attributed their significant finding to the recruitment of a sample of Dutch–French bilinguals living in Belgium, an environment with a high probability of encountering an interlocutor who cannot speak both Dutch and French. Under these conditions, higher sensitivity to linguistic cues would be advantageous in order to determine the appropriate target language. In contrast, the conflicting study by Costa and colleagues (2008) used a sample of Spanish–Catalan bilinguals living in Catalonia, an environment where sensitivity to cues is less crucial as the majority of people can speak both languages. Consistent with these findings, we observed reduced orienting associated with higher levels of L2 proficiency, possibly reflecting the ability of Mandarin–English bilinguals who are more proficient English speakers to communicate with any interlocutor they would encounter in an English-immersive school environment in Mainland China. Given the limited number of previous studies investigating bilingual effects on attentional network function in young people, especially in adolescent samples, further work is needed in order to provide a more complete understanding of the influence of bilingual experience on alerting and orienting.

Cue-specific influence of English proficiency and immersion on executive control

We did not observe evidence in support of a bilingual effect on executive control, likely due to a combination of our observed interaction between cue condition and congruency, as well as the method by which the ANT executive control index is calculated, which involves collapsing across cue conditions (Fan et al., 2002). As shown in Table 2, we did not observe the expected pattern of ANT results when the impact of cue was disaggregated by congruency condition [i.e., no cue > central cue = double cue > spatial cue]. This unexpected finding is further illustrated in Table 3 with incongruent trials associated with faster RTs relative to congruent trials. While interactions between cue and congruency have been reported in a number of studies using the ANT (MacLeod, Lawrence, McConnell, Eskes, Klein & Shore, 2010), they typically do not prevent the identification of the classic "conflict effect". Furthermore, these interactions do not generally prevent the identification of bilingual effects on executive control (Costa et al., 2008; Novitskiy et al., 2019; Pelham & Abrams, 2014; Tao et al., 2011; Yang & Yang, 2016), although null results do exist (Antón et al., 2014; Arredondo et al., 2017; Simonis, Van der Linden, Galand, Hiligsmann & Szmalec, 2020). Indeed, when separate models were built for each cue condition (Sabourin & Vīnerte, 2019), we did observe evidence in support of both improved and reduced executive control associated with different dimensions of bilingual experience. It does, however, need to be noted that even when data were disaggregated by cue condition, incongruent trials resulted in faster RTs relative to congruent trials under center and spatial cue conditions. We attribute our atypical ANT results to the collection of data online with limited control over task conditions. While we have previously replicated Flanker and Simon effects under these same conditions (Privitera et al., 2022), our observed pattern of results suggest that ANT performance, specifically the impact of cue on congruency condition, is perhaps more sensitive to differences in screen distance, eye position, or other participant-level variables. Investigation of the effects of systematic manipulation of screen distance and eye position is needed in order to inform the design of Internet-based assessments of attentional control administered outside of a controlled laboratory setting. Additionally, findings from a recent developmental study using the ANT suggest that the executive control network is not fully stable until late adolescence (Boen et al., 2021). While the average age of our sample is approaching late adolescence, within-participant variability in task performance was likely captured through the inclusion of age as a fixed effect and by-participant random intercepts in our models, and is likely not responsible for our unexpected pattern of ANT results.

Higher bilingualism is not always associated with improved performance

While we expectedly identified a number of null results (e.g., Arora & Klein, 2020; Giovannoli et al., 2020; Lowe et al., 2021), we unexpectedly found evidence in support of reduced task performance associated with higher degrees of bilingualism. Reports of improved performance on non-linguistic tasks by monolinguals compared to bilinguals are rare (Van den Noort, Struys, Bosch, Jaswetz, Perriard, Yeo, Barisch, Vermeire, Lee & Lim, 2019), although exceptions exist (Naeem et al., 2018). In the present study, global increases in RT were associated with higher reported levels of L2/L1 dominance ratio. In the assessment of attentional network function, higher levels of reported L2 immersion as well as language switching frequency were associated with a reduction in the benefit of an alerting cue on task performance. Additionally, higher reported levels of L2 proficiency were associated with reduced orienting effects in response to a spatial cue. Considering the limited research on bilingual effects on attention in adolescents, it is difficult to interpret these results. This is further complicated by the almost exclusive classification of bilingualism as a categorical variable (Luk & Bialystok, 2013), the lack of detailed descriptive data on the myriad dimensions of bilingual experience in studied samples (De Bruin, 2019; Gullifer et al., 2021), and the use of analysis methods that do not allow for the consideration of individual differences in bilingual and non-linguistic experience (Linck & Cunnings, 2015).

Common methodological practices in the investigation of bilingual effects generate conditions under which the identification of authentic effects associated with improved or reduced task performance, as well as authentic null results, becomes challenging if not impossible. To illustrate this point, consider our reported findings that higher L2 proficiency was associated with global DECREASES in RT while higher L2/L1 dominance ratio was associated with global INCREASES in RT. If degree of bilingualism was operationalized as only one of these measures, the conclusions drawn in the present study would be highly misleading. Only through the assessment and modeling of these separable dimensions of language experience do we begin to identify the complex relationship between bilingualism and executive function. When considering our findings in light of how infrequently evidence in support of reduced task performance associated with bilingualism is reported, we are led to a plausible explanation. It is possible that reduced task performance associated with specific dimensions of bilingual language experience is always present, but comparisons between categorical monolingual and bilingual groups, or assessment of a single dimension of language experience prevent identification as these reductions are masked by the presence of improved performance and null effects associated with other dimensions. Evidence in support of a "bilingual advantage" may also result from these same methodological practices, together accounting for the mixed findings that permeate the extant literature. To echo a recent call by Dash and colleagues (Dash, Joanette & Ansaldo, 2022), it is crucial that future studies continue to investigate the contribution of multiple separable dimensions of bilingual language experience in order to understand the influence of bilingualism on cognitive function.

Limitations

Beyond the atypical pattern of results on the ANT detailed above, the present study is potentially limited by the lack of nonverbal intelligence and working memory measures in our models. Individual differences in nonverbal intelligence and working memory are thought to influence the emergence of bilingual effects on cognitive control (Van den Noort et al., 2019). While we did not measure these variables directly, their impact is likely ameliorated by our use of a socioeconomically homogenous sample. Previous work has supported a positive relationship between measures of SES and both nonverbal intelligence and working memory (Alves, Martins & Almeida, 2016; Noble, McCandliss & Farah, 2007). Furthermore, individual differences in these abilities were likely captured in our model through inclusion of random participant intercepts (Linck & Cunnings, 2015). Despite this, the findings reported in the present study should be interpreted with caution. Measures of bilingual language experience, including proficiency, were exclusively self-report in nature (Li et al., 2020). While some may cite this as a limitation of the present study, previous work on the relationship between objective and self-report measures of proficiency suggests that these measures can be considered comparable (Zahodne, Schofield, Farrell, Stern & Manly, 2014; Zhou & Privitera, 2022), especially in samples that are culturally homogenous (Tomoschuk, Ferreira & Gollan, 2019). On a related note, language history details for additional languages beyond Mandarin and English were not collected in the present study. While the number of languages spoken was included as a fixed effect during modeling, it is unknown whether differences in L3+ experience influenced task performance. Results of analyses including participants who reported using only Mandarin and English ($n = 29$) did not differ from those including all participants. Finally, while some studies investigating bilingual effects on cognitive control employ multiple tasks, this is not the case in studies of attention (Privitera & Weekes, 2022). For this reason, we do not expect that our conclusions are limited due to the use of a single measure for attention.

Conclusions

Our findings support that, within a sample of bilinguals, separable bilingual effects on attentional function associated with different dimensions of language experience can be identified. While results were mixed, there is at least some evidence that higher degrees of bilingualism, specifically L2 proficiency and L2/L1 dominance ratio, may confer non-linguistic benefits in monitoring and orienting, respectively. However, these and other dimensions were also associated with reduced performance on other measures of attentional function. Further work is needed in order to better characterize the influence of separable dimensions of bilingual experience on attentional function including how bilingual experience variables are operationalized (e.g., Anthony & Blumenfeld, 2019). On a broader scale, there is a significant need for future investigations of bilingual effects to explore the influence of separable dimensions of language experience on a more comprehensive set of cognitive processes. To draw on Professor Ellen Bialystok's "Swiss cheese" analogy, work of this kind will help identify the "holes" present in bilingualism, allowing for a more complete understanding of how different interventions fit together to support cognitive function.

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Data availability. The data that support the findings of this study, all code used in analyses, and complete model results are available on OSF (DOI 10.17605/OSF.IO/PJVRK) or from the corresponding author (aprivite@qq.-com). All tasks used are freely available online through the Gorilla Experiment Builder: https://app.gorilla.sc/openmaterials/394931. Please note that a free Gorilla account will need to be created in order to preview the tasks.

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