Predicting multilingual effects on executive function and individual connectomes in children: An ABCD study

Young Hye Kwon[a,b], Kwangsun Yoo[b,1], Hillary Nguyen[b], Yong Jeong[a,c,d,1], and Marvin M. Chun[b,1]

[a]Program of Brain and Cognitive Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea; [b]Department of Psychology, Yale University, New Haven, CT 06520-8205; [c]Department of Bio and Brain Engineering, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea; and [d]Korea Advanced Institute of Science and Technology (KAIST) Institute for Health Science and Technology, Korea Advanced Institute of Science and Technology, Daejeon 34141, Republic of Korea

Edited by Judith F. Kroll, University of California, Irvine, CA, and accepted by the Editorial Board October 13, 2021 (received for review June 10, 2021)

While there is a substantial amount of work studying multilingualism's effect on cognitive functions, little is known about how the multilingual experience modulates the brain as a whole. In this study, we analyzed data of over 1,000 children from the Adolescent Brain Cognitive Development (ABCD) Study to examine whether monolinguals and multilinguals differ in executive function, functional brain connectivity, and brain–behavior associations. We observed significantly better performance from multilingual children than monolinguals in working-memory tasks. In one finding, we were able to classify multilinguals from monolinguals using only their whole-brain functional connectome at rest and during an emotional n-back task. Compared to monolinguals, the multilingual group had different functional connectivity mainly in the occipital lobe and subcortical areas during the emotional n-back task and in the occipital lobe and prefrontal cortex at rest. In contrast, we did not find any differences in behavioral performance and functional connectivity when performing a stop-signal task. As a second finding, we investigated the degree to which behavior is reflected in the brain by implementing a connectome-based behavior prediction approach. The multilingual group showed a significant correlation between observed and connectome-predicted individual working-memory performance scores, while the monolingual group did not show any correlations. Overall, our observations suggest that multilingualism enhances executive function and reliably modulates the corresponding brain functional connectome, distinguishing multilinguals from monolinguals even at the developmental stage.

multilingualism | functional connectivity | fMRI | working memory | children

Learning and managing more than two languages is never easy, but the ability to use multiple languages is drawing more and more attention, because it allows multilinguals to understand different cultures and gives social and economic benefits (1, 2). In addition to these benefits, using multiple languages has been suggested to enhance executive functions (3–6), and the executive function advantages of multilinguals can be explained by how our brain juggles multiple languages. Whenever multilinguals engage in linguistic situations (i.e., when they are in a conversation with others or writing a letter), their known languages activate simultaneously even though they choose to use one language over others (7–9). Due to this phenomenon, proper manipulation of cognitive functions, such as focusing on the target language and suppressing other languages at the same time, is crucial for successful communication, and constant usage of these functions lead to better cognitive functioning.

Attention and working memory play a key role in learning and are intimately related. Attention control, the ability to focus on specific stimuli in the environment, is engaged in multilinguals' language use due to the fact that multilinguals need to select and maintain focus on the target language over the other languages. Working-memory domain, the cognitive capacity for holding information to process a given task that is generally involved in managing interference or conflict (10), is another cognitive domain that utilizes language processing of multilinguals. Multilinguals' better attention-control and working-memory capacities have been reported across different age groups, including children (attention: refs. 11 and 12; working memory: refs. 13 and 14), young adults (attention: refs. 15 and 16; working memory: ref. 17), and elders (attention: refs. 18 and 19; working memory: ref. 17).

However, the multilinguals' executive advantages, which have been thought to be robust and well-established byproducts of being multilingual, have recently started to face challenges. A growing body of recent studies has claimed that such advantages are not replicable, reporting no differences in executive functions between monolinguals and multilinguals (20–23). Paap et al. (24), for example, questioned the multilingual benefit on cognitive control skills and discussed that previously reported studies are likely to be biased by uncontrolled confounding factors such as unmatched demographic factors, socioeconomic status (SES), or small sample size. Replication

Significance

Given that using multiple languages incorporates cognitive functions that require a harmony of the whole brain, can we tell whether a child is monolingual or multilingual by only looking at the pattern of functional connectivity? Here, we show that the multilingual experience modulates the functional connections of multilinguals enough to be distinguished from monolinguals. The pattern is distinctive when children are performing an emotional n-back task and even at rest. Furthermore, we found that multilingual children have a stronger relationship between their working-memory functional connectivity and behavior performance than monolinguals. Along with the result that multilingual children outperformed in measures of working memory, we highlight that using multiple languages in early life shapes executive function and functional connections.

Author contributions: Y.H.K., K.Y., Y.J., and M.M.C. designed research; Y.H.K., K.Y., and H.N. analyzed data; Y.H.K., K.Y., H.N., Y.J., and M.M.C. wrote the paper; and K.Y., Y.J., and M.M.C. supervised the project.

The authors declare no competing interest.

This article is a PNAS Direct Submission. J.F.K. is a guest editor invited by the Editorial Board.

[1]To whom correspondence may be addressed. Email: kwangsun.yoo@yale.edu, yong@kaist.ac.kr, or marvin.chun@yale.edu.

This article contains supporting information online at http://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2110811118/-/DCSupplemental.

Published November 29, 2021.

failures brought about a debate on the existence of such multilingual benefits across the human lifespan, including children (21, 22, 25), adults (20, 26, 27), and elders (28, 29). However, the debate regarding multilingualism and its association with executive function has arisen from studies with greater variability in multilingual factors, such as age of the second-language acquisition, proficiency of the second language, and the extent of using an additional language on a daily basis (30).

Throughout the human lifespan, the early stage of life plays a pivotal role in language learning and cognitive development (31, 32). The importance of experience and development in this period is not limited to the dynamic phase but has lifelong impacts on health and behavior (33, 34). Therefore, evidence on multilingualism and its relationship with executive functions in children should be accumulated to better understand the lifespan trajectory of multilingualism and executive control.

Moreover, to comprehend the multilingual impact on cognitive functions, we need to understand the brain mechanisms that underlie the behavioral and cognitive advantages reported for multilinguals. Previous studies have reported multilingualism's effect on brain structure, mainly in the dorsolateral prefrontal cortex, left caudate nucleus, and anterior cingulate cortex, the brain regions that play a role in both linguistic and nonlinguistic cognitive control (refer to refs. 35 and 36 for review). Compared to monolinguals, multilinguals show different functional connectivity patterns between these regions (37). However, examining the whole brain rather than limited regions would give a better understanding on multilingualism's effect on executive functions considering that using languages encompasses a variety of cognitive functions. It has been suggested in general that studying the whole brain could lead to a better understanding of our brain and behavior (38).

A whole-brain functional connectivity, the degree to which brain activities in distinct neural regions are correlated with each other over time, is a reliable measurement that allows researchers to observe how brain regions are engaged in certain cognitive processes (39). The whole-brain functional connectivity pattern, or functional connectome, can be obtained either during task performance (task connectome) or at rest without any explicit tasks (rest connectome). While the task connectome can highlight brain networks engaging in a specific task, the rest connectome shows the brain's intrinsic networks, including the default mode network. The functional connectome is unique to each person and can predict people's personal traits, including fluid intelligence (40, 41), attention (42–44), memory (45, 46), language (47), and personality (48, 49).

Is whole-brain functional connectivity shaped by multilingual experience in children? Can we tell whether a child is monolingual or multilingual by only looking at the brain's functional connectome? Here, we ask whether the whole-brain connectome reflects multilingualism in children and to what extent their cognitive abilities are embedded in the brain. To this end, we start by comparing the behavioral performances of the two cognitive domains, attention and working memory, between multilingual and monolingual groups of children. We analyze a large sample of more than 1,000 children aged between 9 and 10 from the Adolescent Brain Cognitive Development (ABCD) Study, which provides a large and representative sample of the adolescent population with more than 10,000 children from 21 different study sites (50). A result obtained from this large-scale data could add statistically reliable evidence on whether speaking more than one language affects attention and working-memory functions. Next, we investigate whether the two groups have distinct whole-brain functional connectomes that distinguish multilinguals from monolinguals during task performance and at rest. We attempt to classify the two groups using only functional connectomes by means of a support vector machine (SVM). This can inform us whether each group has its own representative connectivity patterns that robustly distinguish one from the other, implying that multilingualism significantly alters the brain's functional connectome. Furthermore, we directly compare the two groups' connectomes to investigate whether different edges are engaged in each group during task performance and at rest. Lastly, as another feature of this study, we attempt to predict the behavioral performance of individual participants in the multilingual and monolingual groups using connectome-based predictive modeling (CPM). This modeling can predict an unseen individual's behavior from their functional brain connectivity based on the model-defined associations between behavior and brain connectivity. In sum, we provide a comprehensive study of multilingualism's effects on behavior, brain, and their associations in the adolescent stage.

Results

Demographic Characteristics. Demographics of participants are shown in Table 1. There was no significant difference of demographic and SES status between the monolingual and multilingual groups in behavioral and functional magnetic resonance imaging (fMRI) analyses after correcting for multiple comparisons. We also confirmed that demographic and SES factors of children analyzed in the fMRI analysis do not differ from the ones in the behavioral analysis (*SI Appendix*, Table S3).

Behavioral Results. Among six different working-memory tasks, the multilingual group performed better on the Rey Auditory Verbal Learning Task (RAVLT) short-delay ($t(1{,}073) = 2.71$, $P = 0.02$ corrected), RAVLT long-delay ($t(1{,}073) = 2.48$, $P = 0.04$ corrected), and recognition task ($t(1{,}073) = 2.80$, $P = 0.02$ corrected). No differences were found in the list-sorting working-memory task ($t(1{,}073)) = 1.82$, $P > 0.05$ corrected), the picture sequence memory task ($t(1{,}073)) = 1.63$, $P > 0.05$ corrected), and the emotional n-back task ($t(1{,}073) = 1.86$, $P > 0.05$ corrected). The flanker task and stop-signal task were used to assess attention control of monolinguals and multilinguals. We found no significant differences between the two groups in the performance of both tasks (flanker task: $t(1{,}073) = 0.36$, $P > 0.05$ corrected; stop-signal task: $t(1{,}073) = -0.86$, $P > 0.05$ corrected). Performance for each task is depicted in Fig. 1. Results of comparing the groups after controlling for demographic and SES factors remained the same as the main results (*SI Appendix*, Fig. S1).

fMRI Results.

Classification results. We trained an SVM model classifying individuals as multilinguals or monolinguals in a ninefold training group and validated the model with the held-out testing group. Each fold was iteratively used as a testing set in 10-fold cross-validation (CV), and this 10-fold CV was repeated 1,000 times by randomly assigning subjects into ten folds.

The SVM model successfully classified multilinguals and monolinguals with accuracies of 80.69% and 81.31% using resting and emotional n-back task functional connectome, respectively. The model trained with the stop-signal task connectome failed to classify the two groups with an accuracy of 50.39%, which was below chance (68.96%) (Fig. 2). Since the monolingual group has twice as many children as the multilingual group and could bias the classification result, we ran an additional SVM analysis after matching the number of children in each group. When trained with a matched number of subjects in each group, our SVM successfully classified the two groups with accuracies of 70.19% and 70.72% using resting and emotional n-back task, respectively, which are significantly better than chance (50%). The model trained with the stop-signal task connectome failed to classify the two groups, with an accuracy of 51.06% (*SI Appendix*, Fig. S2).

Table 1. **Demographics of participants included in behavioral and fMRI analyses**

	Behavior analyses			fMRI analyses		
	Mono	Multi	*p*	Mono	Multi	*p*
Number of subjects	734	341		231	104	
Sex	366 females	167 females	0.79	105 females	50 females	0.66
Age (month)	199.8 ± 7.5	120.3 ± 7.2	0.15	120.1 ± 7.7	121.0 ± 6.6	0.28
Fluid intelligence	10.6 ± 2.7	10.6 ± 2.8	0.34	10.5 ± 2.7	10.7 ± 2.7	0.38
English vocabulary	87.4 ± 7.4	89.9 ± 7.5	0.17	87.4 ± 7.5	89.1 ± 8.3	0.06
Parent education	17.2 ± 1.9	17.5 ± 2.0	0.03	17.1 ± 1.9	17.5 ± 1.9	0.06
Household marriage status*	1.7 ± 1.4	1.6 ± 1.9	0.07	1.6 ± 1.4	1.7 ± 1.5	0.90
Total family income†	7.7 ± 2.3	7.8 ± 2.3	0.95	7.7 ± 2.5	7.7 ± 2.6	0.63

Uncorrected *P* values are shown in the table. All demographic and SES are not significantly different between the two groups after correcting for multiple comparisons.

*Household marriage status: 1 (married); 2 (widowed); 3 (divorced); 4 (separated); 5 (never married); 6 (living with partner); and 7 (refused to answer).

†Total family income: 1 (less than $5 K); 2 ($5 K to 19.9 K); 3 ($12 K to 15.9 K); 4 ($16 K to 24.9 K); 5 ($25 K to 34.9 K); 6 ($35 K to 49.9 K); 7 ($50 K to 74.9 K); 8 ($75 K to 99.9 K); 9 ($100 K to 199.9 K); 10 ($200 K and greater); and 0 (didn't know or refused to answer).

Functional connectome comparison. We compared the functional connectomes between the multilingual and monolingual groups. All 35,778 edges were compared between the groups, and the 268 nodes were clustered into 10 regions to see differences on a macroscale level. In the resting state, the multilingual group showed a significantly stronger connection between the left occipital lobe and prefrontal cortex but had a weaker connection between bilateral occipital lobes compared to the monolingual group after a permutation-based correction (iterations = 1,000). The functional connectome during the emotional n-back task also showed significant differences between the groups. While edges between the left occipital lobe and right subcortical area were stronger in the multilingual group, the connections within the right occipital lobe showed weaker connections compared to the monolingual group. In the stop-signal task, no edges were found to be significantly different between the two groups. The numbers of edges of which strength was significantly different between groups were 2,392 (Multi > Mono) and 4,624 (Mono > Multi) for resting and 3,498 (Multi > Mono) and 5,791 (Mono > Multi) for emotional n-back (a total 35,778 edges in the whole brain). We extracted the top 50 edges that showed the strongest differences in connections for each task and visualized them for clarity (Fig. 3). We also divided the 268 brain nodes into 10 canonical networks for concise visualization of edge difference between the groups (medial frontal, frontoparietal, default mode, motor, visual I, visual II, visual associations, salience, subcortical, and cerebellum) (40) (*SI Appendix*, Fig. S3).

Brain–behavior relationship. To characterize the relationship between the behavioral performance and functional connectome of the two groups, we applied CPM to both task fMRI data, emotional n-back and stop-signal tasks. In the multilingual group, model-predicted emotional n-back scores significantly correlated with observed emotional n-back task scores (median $r = 0.30$, $P = 0.012$ corrected), suggesting that multilinguals show a reliable relationship between brain and behavior. The monolingual group, however, did not show any significant correlation between observed and predicted emotional n-back scores (median $r = 0.17$, $P = 0.06$ corrected; Fig. 4). Furthermore, when we directly compared behavior prediction in the monolingual and multilingual groups, the prediction performance of the multilingual group was statistically better than that of the monolingual group. In the stop-signal task CPM, there was no significant correlation between observed and predicted scores in both groups nor group difference in prediction performance (Fig. 4).

We further asked whether we could see a brain–behavior relationship between the behavioral performance of different tasks within the same cognitive domain (e.g., predict flanker task score using the stop-signal task connectome) and across different cognitive domains (e.g., predict flanker task using emotional n-back connectome) with functional connectome. Because many of these behaviors were measured outside of the scanner, we analyzed rest scan data in addition to task scan data for these CPMs. Accordingly, as a post hoc analysis, we constructed CPMs for every possible combination of imaging and behavioral data, including rest fMRI and fluid intelligence score. This resulted in a total of 25 CPMs per group, every combination of the nine task scores (two attention, six working memory, and fluid intelligence performance) and three fMRI scans (rest, attention, and working memory) except the two CPMs in the main analysis (predicting task performance from their task scans). However, we did not find any significant relationship in any combination after correcting for multiple comparisons (*SI Appendix*, Table S4).

Discussion

Using more than one language requires the engagement of executive functions that use the entire brain. However, it is still largely unknown whether the multilingual experience modulates the brain as a whole. Does using different languages in childhood bring changes in how the whole brain interacts with each? Do multilingual children have a unique functional brain connectivity pattern that distinguishes them from monolingual children? Here, by analyzing data from the large-scale ABCD Study, we investigated whether multilingual and monolingual children show differences in attention and working-memory functions, whole-brain functional connectivity, and the relationship between this performance and functional connectivity.

Multilingualism Enhances Working-Memory Function. In this study, we assessed working-memory function in monolingual and multilingual children by analyzing six behavioral tasks tested in the ABCD dataset. Each task measures different aspects of working-memory function, including episodic working memory, visuospatial working memory, recognition memory, verbal working memory, and nonverbal working memory. We found that multilingual children showed significantly better performance than their monolingual counterparts in the RAVLT short-delay, RAVLT long-delay, and recognition tasks, which measure short- and long-term auditory verbal-memory and recognition-memory abilities, respectively.

Previous studies have reported inconsistent findings on working-memory differences between monolingual and multilingual children

PSYCHOLOGICAL AND COGNITIVE SCIENCES

NEUROSCIENCE

https://doi.org/10.1073/pnas.2110811118

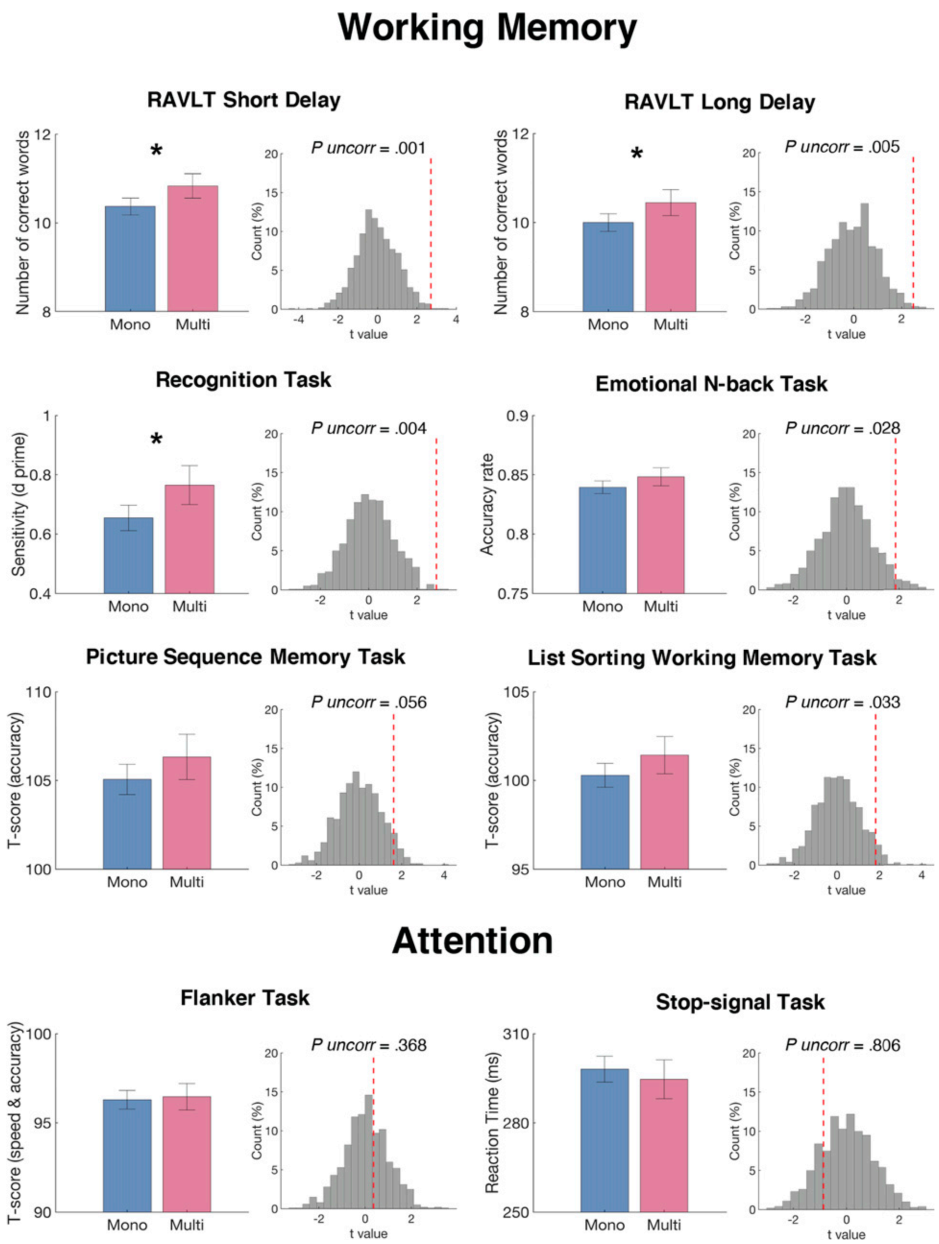

Fig. 1. Behavior performance of the monolingual and multilingual groups in attention and working-memory tasks. Among six working-memory tasks, the multilingual group (red) showed significantly better performance in three tasks, the RAVLT short-delay and long-delay and the recognition task, than the monolingual group (blue). No differences were found in the list-sorting working memory task, picture sequence task, emotional n-back task (working memory domain), flanker task, and stop-signal task (attention domain). Error bars represent the 95% CI. The histogram shows a distribution of the null *t* statistics across 1,000 permutations to which we compared the observed difference (red dotted line) for significance testing (**P* < 0.05, corrected; *P corr:* *p* value corrected for eight tests; and *P uncorr*: uncorrected *P* value for each task).

(5, 14, 51, 52). The conflicting results may be due to the fact that those studies have employed different behavioral tasks and measures to assess working-memory function. For example, while Janus and Bialystok (5) found a multilingual advantage in working-memory function using emotional n-back task, Engel de Abreu (51) did not find any differences when digit recall tasks were used. The ABCD Study allows for a more systematic investigation with six behavioral tasks covering a diverse range of working-memory functions. We observed a general tendency of better performance in multilingual children across all six tasks. Overall, our results suggest that multilingual children at ages 9 and 10 have better working-memory capacities than their monolingual counterparts.

We analyzed the performance of two tasks, stop-signal task and flanker task, to assess attention control between the multilingual and monolingual groups but did not find any significant differences (Fig. 1). The absence of the multilingual advantage in the attention domain replicates previous works with the same tasks and similar-aged children as subjects (22, 53–55). For example, Antón et al. (53) tested attention function of 180 monolingual and 180 multilingual children using the Attentional Network Test, a task that combines the flanker task and cueing task (56), and reported no evidence of a multilingual attention advantage.

The literature shows mixed behavioral results on multilingualism's effect on executive function (refer to ref. 52 for

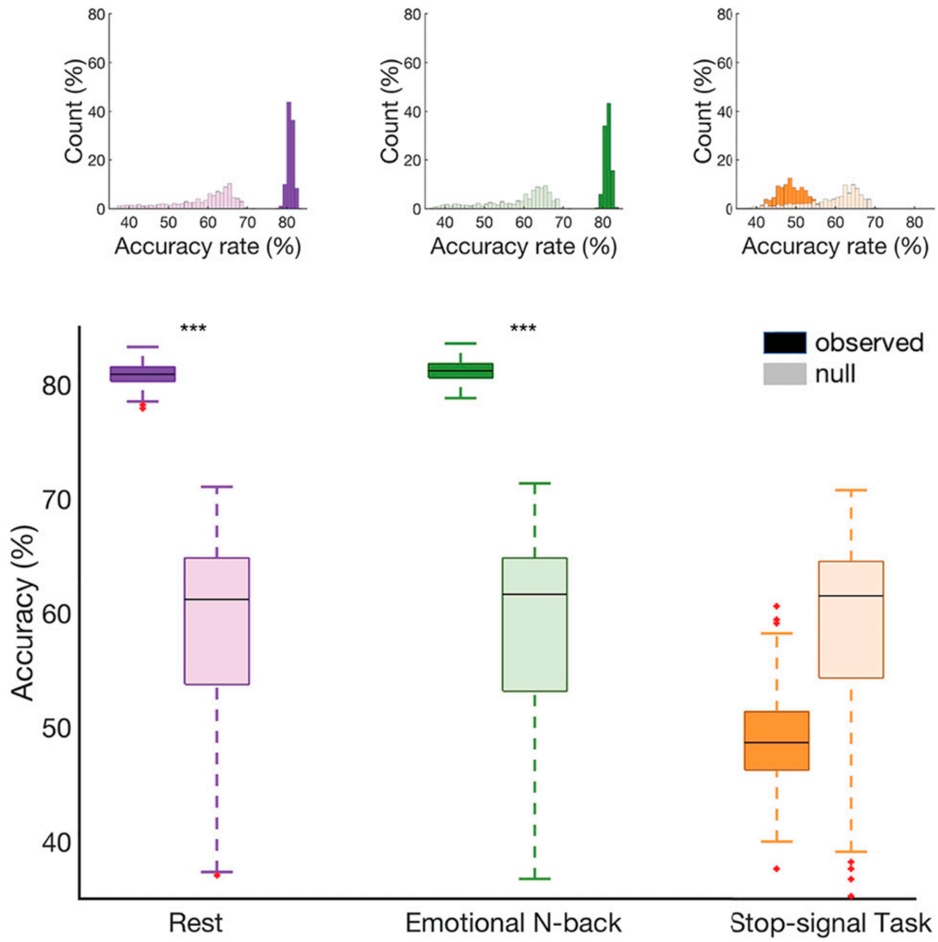

Fig. 2. Classification accuracy rate using an SVM with 10-fold CV. Darker boxes represent observed distributions of each task from 1,000 iterations of 10-fold validation, and lighter boxes indicate null distributions from 1,000 permutations. On each box, the horizontal black line denotes the median, and box edges extend from the 25th to the 75th percentile of each task's distribution. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted using red crosses. The histogram above each task shows the model performances across the observed (darker bars) and null distribution (lighter bars) (***$P < 0.001$ based on 1,000 permutations).

review). Although the multilingual children in this study showed significantly better performance in only three out of eight tasks, it is worth noting that none of the tasks were favorable to monolinguals. This consistent tendency obtained from a large sample size suggests that our findings of multilinguals' better task performances are unlikely due to a Type I Error, which has been argued as a potential cause of better executive functioning in multilinguals (24). This supports reliable effects of multilingualism on executive functions in 9- and 10-y-old children, but further studies should be conducted to investigate under what circumstance such effects will occur and not occur. Also, it is important to note that although we classified each task into conventional preexisting categories (i.e., attention and working memory) to connect them to these broad umbrella concepts, each task does not correspond to a specific, one-to-one cognitive process but rather requires a mixture of multiple processes. For example, the stop-signal task also measures response inhibition while the flanker task measures conflict resolution. A better understanding of how multilingual experience affects executive function should avoid a strict categorization of tasks as reflecting specific cognitive processes (57, 58).

Multilinguals Have Distinct Functional Connectome during Working-Memory Task and at Rest. In addition to behavioral differences in working-memory function, we examined whether different language experience alters the brain's functional connections, resulting in distinct patterns of functional connectome between monolinguals and multilinguals. By training a simple SVM model, we were able to classify the two groups using only their resting-state functional connectome. This implies that the multilingual experience reliably modulates and is reflected in the intrinsic functional connectome at the developmental period. Considering that the children are 9 and 10 y old, it is interesting that even such a short language experience causes a difference in functional connectome and makes it representative of each group.

Functional connectome observed during working-memory task performance could also successfully classify the two groups. Although the group difference in the emotional n-back task performance became insignificant after correcting for multiple comparisons, the difference was significant before the correction. Moreover, we observed that the emotional n-back task performance correlates with all of the other working-memory tasks (*SI Appendix*, Table S5). Given these findings, we may hypothesize that various working-memory functions modulated functional connectome altogether to make the multilingual group distinguishable from the monolingual group. In contrast, the classification rate using functional connectome while performing an attention task was only at chance level, suggesting that monolinguals and multilinguals have indistinguishable functional connectivity patterns when performing an attention task. Although it is difficult to draw conclusions from this null result,

https://doi.org/10.1073/pnas.2110811118

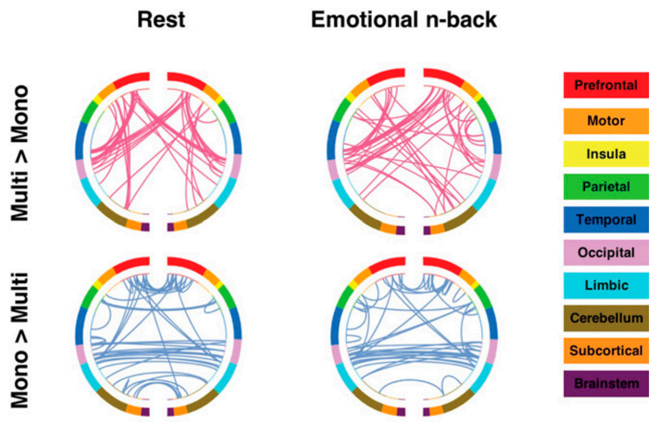

Fig. 3. Circle plots organized into macroscale regions showing differences in whole-brain functional connectome in two states: rest and emotional n-back (working memory). The result of the stop-signal task (attention) is not shown here, because monolinguals and multilinguals did not show any differences. In each circle plot, the left half of the circle shows regions in the left hemisphere, and the right half shows regions in the right hemisphere. The *Top* row depicts edges that are significantly stronger in the multilingual group, and the *Bottom* row shows edges that are significantly stronger in the monolingual group for each fMRI data ($P < 0.001$, corrected using permutation). For clarity, the top 50 edges that show the strongest differences in connections between monolinguals and multilinguals are presented in the circle plots.

it is interesting that functional connectivity patterns of both groups become less distinct when performing an attention task compared to when performing a working-memory task and at rest.

Multilingualism Affects Intrinsic Rest Connectivity of Prefrontal Cortex and Working-Memory Task–Related Connectivity of Subcortical Area. Stronger connections between the prefrontal and occipital brain regions in the multilingual brain at rest suggests increased involvement of the brain areas responsible for executive function and those for language preprocessing and/or communication between them. The prefrontal cortex is known to play a critical role in orchestrating complex cognitive functions, including working memory and attention control (refer to ref. 59 for review), and the occipital lobe is primarily responsible for visuospatial processing but is also engaged in language processing (60). Multilinguals are more exposed to different orthography and phonology than monolinguals in their daily life, and executive functions may help regulate the additional demands on linguistic processing. Hence, it is plausible that multilinguals have a stronger connection between the executive function regions that is even reflected in the brain at rest. Previous literature reported that multilinguals have more bilateral activation than monolinguals, especially in the cingulate cortex and corpus callosum, for both children and adults (61, 62). A recent study comparing whole-brain resting functional connectivity, however, reported stronger connectivity in the bilateral occipital cortex in monolinguals than multilinguals (63). Our monolingual group result, also showing stronger connectivity within the occipital regions, is in line with Fan et al. (63), but the discrepancy with other studies showing more bilateral engagement in multilinguals might be due to differences between activation and connectivity measures, different methods of calculating functional connectivity, different brain atlases, or different age groups.

During the emotional n-back task, multilinguals showed stronger connections between the left occipital lobe and the right subcortical area but weaker connections within the right occipital lobe than monolinguals. The subcortical regions are known to be engaged in syntax and verbal working memory (64–66), and the occipital areas play a role in visuospatial processing as mentioned above. Grundy et al. (67) proposed a bilingual anterior-to-posterior and subcortical shift (BAPSS) model that argues that multilinguals recruit more subcortical regions than monolinguals as their second-language proficiency increases, especially when they are performing nonverbal executive tasks. The emotional n-back task that we analyzed in this study taps nonverbal working memory, and the stronger connectivity between the subcortical area and occipital lobe in the multilingual group is in line with the BAPSS model. It is interesting that such connections show significant differences between the language groups, given the nonsignificant difference in behavior performance. Coinciding with behavioral results in this study, functional connectivity while performing the stop-signal task did not show any difference between the groups (Fig. 3). However, it is worth reminding that functional connectivity at rest showed significant differences. Thus, it might be possible that monolinguals and multilinguals experience different functional connectome reconfigurations from the resting state to an attention task state, and future studies could uncover this intriguing possibility.

Multilinguals Show a Reliable Brain–Behavior Relationship in Working-Memory Function. Previous studies examined the effect of multilingualism on behavior performance or within an a priori set of brain regions/networks. However, how the multilingual experience changes the extent to which behavior is reflected in the functional connectome is still largely unknown. We adopted the CPM procedure to establish and validate a brain–behavior relationship at the level of the individual. CPMs trained on multilinguals' emotional n-back working-memory task connectome successfully predicted the task performance of previously unseen multilinguals. On the contrary, CPMs trained with the monolingual group could not predict the unseen children's task performance. The contrast in CPM prediction between groups suggests that the multilinguals' working-memory connectome reflects their behavior, while the monolinguals' connectome does not convey behaviorally relevant information that can be extracted by a simple linear approach.

Previous studies have reported that attention and working memory can be predicted using resting and task connectivity in an adult group and even in neurodegenerative disease patients (43–45, 68). Avery et al. (45) used CPM and showed that functional connectivity while performing the n-back working-memory task can predict performance in healthy adults. Another work attempted to predict list-sorting working-memory performance using resting-state connectivity with different age-range groups, including a children group of ages 6 through 10 (68). The study reported that CPMs trained with the children group did not predict working-memory performance, while CPMs trained on the adult group showed accurate predictions. Along with these previous findings, our results of successful prediction of the working-memory task behavior only in multilingual children, but not in monolingual children, suggests a possibility that the multilingual experience accelerates brain development, resulting in multilingual children having a more adult-like, matured brain functional organization than monolinguals.

Notably, for both behavior and brain connectivity, we observed consistent differences in the working-memory domain between multilingual and monolingual children. To assess working-memory function in the brain, we used emotional n-back task fMRI data, which engages working-memory and emotion-regulation processes. A previous study provided evidence that frontoparietal activity reflects working-memory performance and that activation in this region is specific to working memory (69). Although we cannot completely disentangle emotion processing from working-memory function,

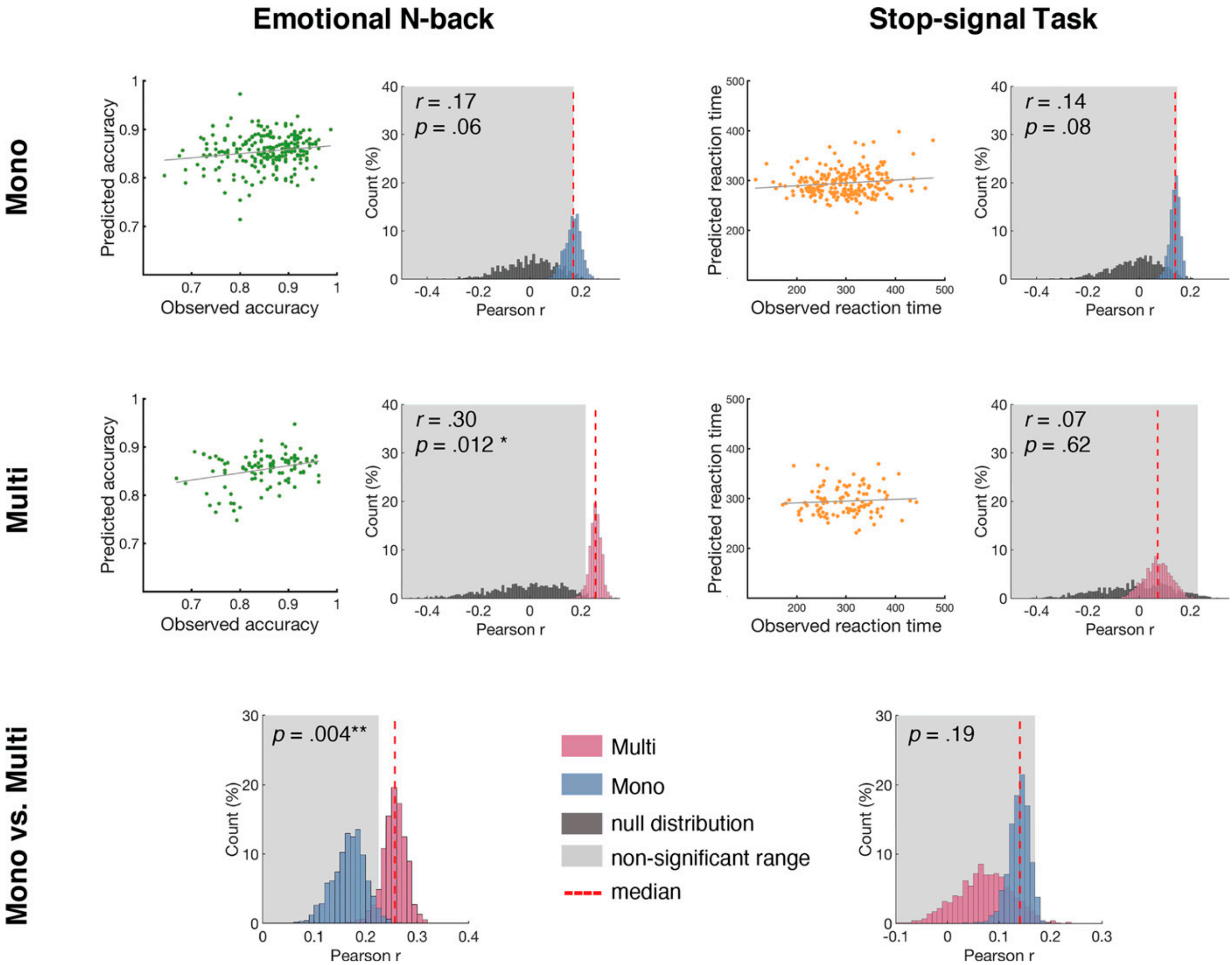

Fig. 4. CPM performance with 10-fold CV. The *Left* column shows the CPM performance in the emotional n-back task, and the *Right* column shows the model performance in the stop-signal task. The first row presents CPM performance of the monolingual group, and the second row presents results of the multilingual group for each task. The scatter plots show the relationship between observed and predicted task scores. The histograms show the model performance across 1,000 iterations of the observed and null model performance. In each histogram, dark gray bars indicate a distribution of the null model performance from 1,000 permutation, and colored bars indicate a distribution of the observed model performance from 1,000 repetitions (blue: monolingual, red: multilingual). The red dashed line indicates the median value of the observed distribution, and the shaded area shows a range of non-significance after correcting for multiple comparisons. That is, the model prediction is considered successful if the red dashed line is located outside of the shaded area. The last row represents observed model performance of the monolingual and multilingual groups across 1,000 iterations. The monolingual group's distribution is represented in blue, and the multilingual group's distribution is represented in red. The red dashed line indicates the median value of the group with the higher *r* distribution, and the shaded area shows a range of nonsignificance after Bonferroni corrections for multiple comparisons (*$P < 0.05$; **$P < 0.01$ based on 1,000 permutations).

given our findings that multilinguals showed stronger functional connections between the frontoparietal region and other networks (*SI Appendix*, Fig. S3) instead of engagement of the subcortical network that are known to work with emotional processing (refer to ref. 70 for review), we cautiously suggest that working-memory function rather than emotional regulation is the component that shows the difference between monolingual and multilingual children. Our fMRI results might not generalize to different working-memory tasks, because we only studied emotional n-back task functional connectivity. That is, we observed that the multilingual language experience changes brain connectivity while performing the emotional n-back task, and whether it holds to a working-memory task in general should be further examined.

In this study, we analyzed a large group of children with an age range of 9 to 10. Given that the developmental stage is a critical period undergoing massive behavioral and neuronal changes, the narrow age range allows us to capture monolingual and multilingual children's representative behavior and neuronal features at the very precise time of the developmental stage, which is a great benefit of our study. However, our results should not be generalized to all children at the developmental stage, and further longitudinal studies are needed to better understand how multilingualism shapes executive functions and the brain over time. In addition, we used a simple definition of "multilingual," by binary-dividing children based on self-reporting, although we paid extra care by combining surveys from both child and their parents. The definition of "multilingual" is known to affect findings in multilingual studies; therefore, if the definition changes, different results may emerge (71). Moreover, we did not take important factors in multilingualism study, such as the age of acquisition, proficiency of the second language, and the extent of using an additional language on a daily basis into account due to insufficient data (72). However, children in the current study are likely early multilinguals, considering their narrow and young age.

Here, we explored whether a multilingual language experience affects cognitive abilities, whole-brain functional connectivity, and their association. Our observations suggest that the multilingual experience benefits executive function in children and also induces a reliable modulation in the whole-brain functional connectome.

Materials and Methods

Participants. We used data from the ABCD Study. The ABCD Study is a longitudinal and multi-sited study of brain development and physical and mental health of adolescents that releases curated data annually (50, 73). In this study, we used baseline, year-one behavioral, demographic, and imaging data from the curated annual release 2.0 (children at ages 9 through 10, $n = 11{,}875$). We excluded children who showed signs of hydrocephalus or brain herniation or had abnormal findings or abnormal anatomical variants of no clinical significance in their MR findings ($n = 11{,}228$). We also excluded children diagnosed with neurological disorders, including cerebral palsy, tumor, stroke, brain aneurysm, brain hemorrhage, subdural hematoma, schizophrenia, autism spectrum disorder, intellectual disability, or other reported psychological conditions or concerns. Based on the ABCD Parent Medical History Questionnaire, we further excluded children with a history of epilepsy, multiple sclerosis, and sickle cell anemia ($n = 10{,}728$).

We divided children into monolingual and multilingual groups based on the self-report language history survey (ABCD Youth Acculturation Survey Modified from Phen X) (74) and parent demographics survey (ABCD Longitudinal Parent Demographics Survey). In this study, the term "multilingual" is defined as any children who speak or understand any language in addition to their native language, English. We chose this definition because the survey does not include a question that asks how many languages a child understands; thus, we could not determine whether a child is a bilingual who speaks and understands only two languages or which children speak and understand three or more languages. Children were asked to answer the question, "Besides English, do you speak or understand another language or dialect?" For children who answered "no" to this question, we further used answers from their parents provided by the ABCD dataset to confirm their native language. Parents were asked "What is your child's native language?" and only children whose parents answered "English" to this question were included in the monolingual group and used in our analyses. In other words, the first language of all monolingual children was limited to English to minimize the heterogeneity in language history between monolingual and multilingual children ($n = 3{,}064$). Language typology, classification of languages according to their structural similarities, is a possible confounding factor that can lead to engagement of different executive functions when acquiring or processing additional languages (75), and restricting children's first language allows us to lessen language typology effects. The monolingual group included children who reported English as their native language and rated their English proficiency at the excellent level. Parents also verified that English was their children's native language. The monolingual children and their parents reported that the children did not understand nor spoke a language other than English. The multilingual group included children who reported their first language as English, rated their English proficiency at the excellent level, and had their parents confirm English as their children's native language. In addition, the multilingual children and their parents reported that the children could understand or spoke other languages. Among the children classified as multilinguals, children who reported that they spoke or understood American Sign Language (different modality) or Native American English (dialects of English spoken by American Indians and Alaska Natives) as their second language were excluded. Since information on the age of second-language acquisition or fluency of the second language was not available from the dataset, we did not take these variations into account for the analyses.

As handedness is highly associated with hemispheric language dominance (76), we included only right-handed children from both the monolingual and multilingual groups ($n = 2{,}405$). To avoid confounds introduced by family structure, we used only one child per family by selecting the first child after sorting their National Database for Autism Research Global Unique Identifiers in alphabetical order ($n = 1{,}967$). We included subjects who had all task scores available and acceptable, including the RAVLT short-delay and long-delay, flanker task, stop-signal task, list-sorting memory task, picture sequence working-memory task, emotional n-back task, recognition task, picture vocabulary test, and matrix reasoning ($n = 1{,}124$). Children with a behavioral performance lower or higher than 3 SDs from the total group mean in any task were excluded as outliers ($n = 1{,}076$). To take SES into consideration that may affect cognitive abilities in children (77), we excluded children with missing SES factors, including annual household income, parents' marital status, and parents' highest education level. For parents' education, we averaged the number of years of the two parents' education if both were reported, or we used the number of years from one parent if only one parent's education level was available. The detailed information on each SES factor is presented in *SI Appendix*, Table S1. The final subject pool consisted of 1,075 children, including 734 monolinguals and 341 multilinguals.

To investigate whether multilingualism improves executive functions, we focused on the two cognitive domains of attention and working memory. We analyzed behavioral performance from eight behavioral tasks: six out-of-scanner and two in-scanner tasks (50, 73). Attention control was assessed with the stop-signal task (in-scanner) and the NIH Toolbox flanker task scores. Working-memory functioning was assessed with the emotional n-back (in-scanner), recognition task, RAVLT short-delay, RAVLT long-delay, the NIH Toolbox list-sorting working-memory task, and the NIH Toolbox picture sequence memory test performances.

Attention. *The NIH Toolbox flanker task.* The flanker task measures attention and inhibition as well as a conflict-monitoring response (50, 78). In each trial, children are presented with a string of five arrows. The two left and two right arrows are flankers, and the middle arrow is the target arrow that children are instructed to pay attention and respond to. In the congruent condition, the four flankers and the target arrow are pointing to the same direction (left or right), and in the incongruent condition, the flankers and the target arrow point in opposite directions. Performance is measured by accuracy and reaction time.

Stop-signal task. The stop-signal task (79) measures impulsivity as well as impulse control and inhibition (73). In this task, children see an arrow either pointing to the left or to the right on the screen. They are instructed to indicate which direction the arrow is pointing by pressing a button. This task includes two conditions. At the beginning of each trial, children see a leftward or rightward pointing arrow. If the arrow is followed by the up-right arrow ("Stop Signal"), children have to withhold their response, which is the "Stop" condition. This condition occurs for 16.67% of the total trial. If the arrow is not followed by a "Stop" arrow, then the children are instructed to make a response by pressing a button. This is the "Go" condition, which comprises a great portion of the total trial. The stop-signal task was collected during fMRI scanning, and it consisted of two runs, with each run containing 180 trials. Performance is measured by mean stop-signal reaction time.

Working memory. *Rey Auditory Verbal Learning Test—short delay and long delay.* The RAVLT measures auditory learning and memory (50, 80). Children listen to a list of 15 unrelated words five times followed by 15 distractor words. Children are asked to recall as many words as possible from the second list. Then, they are asked to recall as many words as possible from the first list (short delay). To test long-term retention, children are asked again to recall the words from the first list with a 30-min delay (long delay). The number of correctly recalled words on the short- and long-delay tests are measured.

The NIH Toolbox list-sorting memory task. The list-sorting memory task measures working memory (50, 81). Children are shown a series of pictures of animals or foods of different sizes. In the first trial, children are shown two animals and asked to repeat them back in the order of size, small to large. Depending on the children's performance, the number of items increases up to seven items. After the single-item test, they are shown animal and food items interleaved with each other. They are first asked to repeat the list of animal items back in order from smallest to largest and then asked to repeat the food items in order of size. The task starts with two items and increases up to seven items depending on the children's performance. The performance is measured by the number of correct responses.

The NIH Toolbox picture sequence working-memory task. The picture sequence working-memory task measures episodic working memory (82). Children are presented 15 pictures of sequential events or activities and asked to reproduce the events in the same order they were presented. The performance is measured by accuracy of the cumulative number of neighboring picture pairs that are correctly answered over three learning trials.

Emotional n-back task. The emotional n-back task measures working memory and emotional regulation processes (73). The task consists of two runs of eight blocks each: four 0-back and four 2-back conditions. In the

0-back condition, children are asked to press a "match" button whenever the current image matches a target image that is shown at the beginning of the trial. Children are asked to press a "no match" button if the current image does not match with the target image. In the 2-back condition, children are instructed to press a "match" button when the current image is the image that they saw two images before, and "no match" otherwise. Performance is assessed with mean accuracy rate of 0-back and 2-back conditions. The n-back task was collected during fMRI scanning.

Recognition task. The recognition task is done using the stimuli presented in the emotional n-back task, and it measures short-term memory processes (73, 83). In this task, children see 96 images, 48 new and 48 old images, that are presented in the emotional n-back task in the scanner, and they are asked to classify whether the image is "old" or "new." Mean sensitivity (d') is used for performance score.

Behavioral Analysis. Since SES may affect cognitive abilities in adolescents, we confirmed that the monolingual and multilingual groups did not differ in major elements of SES, annual household income, parents' marital status, and parents' education level (Table 1). As all three SES factors did not differ between the groups, we performed a two-sample *t* test to compare the behavioral performance of the monolingual and multilingual groups. To determine the statistical significance of the difference, we used a nonparametric permutation test. We randomly shuffled behavior scores across the groups, separated the shuffled scores into two groups according to the different numbers of subjects in each group, and ran a two-sample *t* test to obtain a null t-value in each permutation. We repeated this procedure 1,000 times and compared the observed t-value to a null distribution from 1,000 permutations. Family-wise error (FWE) for multiple comparisons was controlled using maximal statistic during the permutation test (84). The maximum null t-value was selected in each iteration, and the resulting 1,000 maximum null t-values were compared to the observed t-value. The FWE-corrected significance of the observed t-value was calculated using the following equation: $p(t) = ((\text{the number of null max t-values} > \text{the observed t-value}) + 1)/1{,}001$.

To ensure that demographic and SES factors do not confound this analysis, an additional analysis was carried out after regressing out these variables from each behavioral performance. We compared residuals from the multiple linear regression using a two-sample *t* test. A significance test and FWE correction were performed using the same procedure as stated above. All behavioral analyses were performed in MATLAB R2018a.

fMRI Analysis.

MRI parameters, preprocessing, and quality control. For fMRI analysis, we further selected subjects who had an anatomical image and at least one usable run for each fMRI data, including resting-state, emotional n-back, and stop-signal tasks among the 1,075 children used in the behavioral analysis. The ABCD MR images were collected from three 3T scanners (Siemens, General Electric 750, and Philips). Here, we used images acquired only from Siemens and General Electric 750 due to incorrect postprocessing of the fMRI data obtained on the Phillips scanner at the time of analysis ($n = 938$). We additionally excluded children with images that failed to pass image quality control and rated moderate or severe in motion score determined with the curated data release 2.0 ($n = 760$).

We obtained minimally processed high-resolution anatomic scans, four resting-state fMRI runs, and two task fMRI runs for each of the stop-signal task and emotional n-back task from the ABCD Study. Functional images were collected with the following parameters: TR= 800 ms, TE = 30 ms, Flip angle = 52 degrees, FOV = 216 × 216, voxel size = 2.4 mm^3, multiband slice acceleration factor = 6, and 60 slices acquired in the axial plane. Detailed image acquisition parameters can be found in the previous studies (73, 85).

The minimally processed fMRI images were additionally processed using AFNI (86) and MATLAB R2018a. The processing procedure included the following steps: Removing the first 10 volumes; censoring of volumes in which more than 10% of voxels were outliers; censoring of volumes for which the Euclidean norm of the head motion parameter derivatives were greater than 0.2 mm; despiking; slice-time correction; motion correction; regression of mean signal from the cerebrospinal fluid, white matter, and whole brain, and 24 motion parameters. FMRI images were then aligned to T1 and normalized to Montreal Neurological Institute (MNI) space. All processed functional images were visually inspected for image quality control, and runs that had passed image quality control were included in the analyses. We excluded children who failed visual quality control or had excessive head motion (>3-mm maximum head displacement and >0.15-mm mean framewise displacement after censoring) from the fMRI analyses. As a result, 335 children, including 231 monolinguals and 104 multilinguals, were used in the fMRI analyses (Table 1). The detailed information on each SES factor is presented in *SI Appendix*, Table S2.

Whole-brain functional connectivity matrix. The whole-brain functional connectivity matrices were generated using a 268-node whole-brain atlas (87). For each child, we averaged voxel-wise time-series signals for each node and calculated Pearson's correlation between every pair of the 268 nodes. The pairwise correlation coefficients were then Fisher z-transformed, resulting in a 268 × 268 symmetrical, whole-brain, functional connectivity matrix for each child and for each fMRI. The ABCD fMRI scan includes four runs of resting state and two runs of each task fMRI. We calculated the connectivity matrices for each run separately and averaged them across all runs to make one matrix for each rest and task fMRI. For those who did not have full runs or had runs that failed in quality control, we constructed the connectivity matrices of the available runs and averaged them to make one connectivity matrix for each fMRI data. As a result, every individual had three connectivity matrices: resting-state, stop-signal, and emotional n-back.

To cope with head motion artifacts in the fMRI analyses, we regressed mean frame-to-frame displacement out from the functional connectivity of each fMRI scan (resting-state, emotional n-back, and stop-signal task) using a linear regression. The residuals of this regression were then used as functional connectivity matrices in the fMRI analyses.

Connectome-based classification. We investigated whether multilingualism modulates the whole-brain connectome in a consistent way. If we can distinguish the two groups using only the whole-brain connectome, we can conclude that the brain's functional organization embodies multilingualism. We used an SVM, a supervised machine-learning technique that is capable of binary classification (88, 89), to classify children into monolingual and multilingual groups based on their connectome. We applied 10-fold CV to train and validate the SVM model. We held out onefold (10% of monolinguals and 10% of multilinguals) for model validation and trained a model with the remaining nine folds (90% of monolinguals and 90% of multilinguals). In the training set, we first defined a set of brain networks (principal components) by employing principal component analysis. All computed principal component scores of training individuals were used to train the SVM model. We used the trained SVM to classify whether a child in the testing group is monolingual or multilingual based on estimated principal component scores of the testing sample. The scores of the testing samples were estimated by applying the principal component coefficients of the training set to the testing samples' whole-brain connectivity. Each of the 10 folds was iteratively used as a testing set. The classification accuracy rate was calculated by averaging accuracies across 10 folds of each iteration. We repeated this classification procedure 1,000 times to estimate the distribution and reliable statistic for each fMRI data (resting-state, emotional n-back, and stop-signal task).

An unbalanced number of subjects between groups in a training set can cause a problem in classification analyses; that is, when one group has more subjects than the other, the classifier could be biased to the larger group and result in making a model favoring the larger group. We addressed this issue in two ways. First, we applied weight for each observation proportional to each class probability, which led to heavy penalties to the larger group (monolinguals) and less to the smaller group (multilinguals) when training the model (90). A second approach was to randomly subsample from the larger group to match the size of the smaller group.

Functional connectivity comparison between multilingual and monolingual groups. We then examined whether the ability to use multiple languages affects functional connectivity at rest or during task performance. The functional connectivity matrices in each fMRI data were compared between groups using a two-sample *t* test (two-tailed). The maximal statistic permutation procedure was used to assess the significance and correct for multiple comparisons (iterations of 1,000).

Brain–behavior relationship. We further question whether the brain–behavior relationship in monolingual and multilingual children differs. If we see diverging relationship patterns from each group, this would suggest that multilingualism modulates relationship between behavior and the functional connectome. Correlation is a representative method to examine relationship between two variables. However, it is important to validate any findings from using correlation analysis in out-of-sample data, demonstrating a reliability of in-sample findings (91). For this purpose, a method that is capable of both revealing and cross-validating a result would be useful. We thus employed CPM, which is a simple yet strong data-driven protocol. This modeling approach develops computational models of brain–behavior relationships from functional connectivity (92). Previous works show that CPM can predict individual differences in attention (43, 44) and working memory (45) in adult groups. By using this method, we can characterize and compare brain–behavior relationships of the two groups as well as cross-validate results if our observations reliably extend to out-of-sample data by predicting the testing samples' behavior of interest based on associations defined in the training samples.

PSYCHOLOGICAL AND COGNITIVE SCIENCES

NEUROSCIENCE

https://doi.org/10.1073/pnas.2110811118

We used individual task performances and fMRI data of the emotional n-back and stop-signal tasks to construct the CPM for each task. We applied 10-fold CV to train and validate the CPM. In a training set, we selected edges that were significantly correlated with task performance with a threshold of $P < 0.01$ (Pearson's correlation), resulting in both positively and negatively correlated network masks. Connectivity edge weights in each mask were averaged to generate positive and negative network strengths for each child. A general linear model was then fitted between task performance (dependent variable) and the two networks' strengths (predictors). We applied the trained CPM to the testing group to predict the testing group's behavior scores. The same procedure was done for each task (emotional n-back and stop-signal task) and repeated 1,000 times by randomly assigning subjects into 10 folds.

To assess the significance of the model's performance, we performed 1,000 permutations of 10-fold CV in which subjects were shuffled within each group, constructing a null distribution of the model performance. The significance of the observed model performance was calculated by comparing the median of the observed *r* values from 1,000 iterations of 10-fold divisions and the null distribution using the following equation:

$$p(r) = ((\text{the number of permuted null } r > \text{a median of the observed } r) + 1)/1001.$$

We corrected for multiple hypothesis testing using Bonferroni correction.

Data Availability. Data used in the preparation of this article were obtained from the ABCD Study (https://abcdstudy.org), held in the National Institute of Mental Health Data Archive (NDA). This is a multisite, longitudinal study designed to recruit more than 10,000 children age 9 to 10 and follow them over 10 y into early adulthood. A listing of participating sites and a complete listing of the study investigators can be found at https://abcdstudy.org/consortium_members/. The ABCD data repository grows and changes over time. The ABCD data used in this report came from NDA DOI 10.15154/1504041. ABCD consortium investigators designed and implemented the study and/or provided data but did not necessarily participate in the analysis or writing of this report. This manuscript reflects the views of the authors and may not reflect the opinions or views of the NIH or ABCD consortium investigators. Scripts for data analyses are available for download from GitHub, https://github.com/younghye87/Kwon_multilingualism.

ACKNOWLEDGMENTS. This work was supported by the Yale Faculty of Arts and Sciences MRI Program, funded by the Office of the Provost and the Department of Psychology; NIH Grants MH108591 (to M.M.C.); the Basic Research Laboratory Program (NRF-2020R1A4A1018714, to Y.J.), funded by the Korean Government through the National Research Foundation; and the Technology Innovation Program (20012464, to Y.J.) funded by the Ministry of Trade, Industry and Energy (Korea). The ABCD Study is supported by the NIH and additional federal partners under award nos. U01DA041048, U01DA050989, U01DA051016, U01DA041022, U01DA051018, U01DA051037, U01DA050987, U01DA041174, U01DA041106, U01DA041117, U01DA041028, U01DA041134, U01DA050988, U01DA051039, U01DA041156, U01DA041025, U01DA041120, U01DA051038, U01DA041148, U01DA041093, U01DA041089, U24DA041123, and U24DA041147. A full list of supporters is available at https://abcdstudy.org/federal-partners.html.

1. L. Aronin, D. Singleton, Multilingualism as a new linguistic dispensation. *Int. J. Multiling.* **5**, 1–16 (2008).
2. T. Guo, F. Liu, B. Chen, S. Li, Inhibition of non-target languages in multilingual word production: Evidence from Uighur-Chinese-English trilinguals. *Acta Psychol. (Amst.)* **143**, 277–283 (2013).
3. M. M. Martin-Rhee, E. Bialystok, The development of two types of inhibitory control in monolingual and bilingual children. *Bilingualism* **11**, 81–93 (2008).
4. R. Barac, E. Bialystok, Bilingual effects on cognitive and linguistic development: Role of language, cultural background, and education. *Child Dev.* **83**, 413–422 (2012).
5. M. Janus, E. Bialystok, Working memory with emotional distraction in monolingual and bilingual children. *Front. Psychol.* **9**, 1582 (2018).
6. H. Yang, S. Yang, Are all interferences bad? Bilingual advantages in working memory are modulated by varying demands for controlled processing. *Biling. Lang. Cogn.* **20**, 184–196 (2017).
7. D. Green, Mental control of the bilingual lexico-semantic system. *Biling. Lang. Cogn.* **1**, 67–81 (1998).
8. J. F. Kroll, P. E. Dussias, C. A. Bogulski, J. R. V. Kroff, "Juggling two languages in one mind. What bilinguals tell us about language processing and its consequences for cognition" in *Psychology of Learning and Motivation*, B. H. Ross, Ed. (Academic Press, 2012), vol. 56, pp. 229–262.
9. W. J. B. Van Heuven, T. Dijkstra, J. Grainger, Orthographic neighborhood effects in bilingual word recognition. *J. Mem. Lang.* **39**, 458–483 (1998).
10. M. J. Kane, A. R. A. Conway, T. K. Miura, G. J. H. Colflesh, Working memory, attention control, and the N-back task: A question of construct validity. *J. Exp. Psychol. Learn. Mem. Cogn.* **33**, 615–622 (2007).
11. L. L. Kapa, J. Colombo, Attentional control in early and later bilingual children. *Cogn. Dev.* **28**, 233–246 (2013).
12. S. Yang, H. Yang, Bilingual effects on deployment of the attention system in linguistically and culturally homogeneous children and adults. *J. Exp. Child Psychol.* **146**, 121–136 (2016).
13. E. Blom, A. C. Küntay, M. Messer, J. Verhagen, P. Leseman, The benefits of being bilingual: Working memory in bilingual Turkish-Dutch children. *J. Exp. Child Psychol.* **128**, 105–119 (2014).
14. J. Morales, A. Calvo, E. Bialystok, Working memory development in monolingual and bilingual children. *J. Exp. Child Psychol.* **114**, 187–202 (2013).
15. A. Chung-Fat-Yim, G. B. Sorge, E. Bialystok, The relationship between bilingualism and selective attention in young adults: Evidence from an ambiguous figures task. *Q. J. Exp. Psychol. (Hove)* **70**, 366–372 (2017).
16. A. Costa, M. Hernández, N. Sebastián-Gallés, Bilingualism aids conflict resolution: Evidence from the ANT task. *Cognition* **106**, 59–86 (2008).
17. E. Bialystok, G. Poarch, L. Luo, F. I. M. Craik, Effects of bilingualism and aging on executive function and working memory. *Psychol. Aging* **29**, 696–705 (2014).
18. J. Abutalebi *et al.*, Bilingualism provides a neural reserve for aging populations. *Neuropsychologia* **69**, 201–210 (2015).
19. G. Ong, D. K. Sewell, B. Weekes, M. McKague, J. Abutalebi, A diffusion model approach to analysing the bilingual advantage for the Flanker task: The role of attentional control processes. *J. Neurolinguistics* **43**, 28–38 (2017).
20. E. Antón, M. Carreiras, J. A. Duñabeitia, The impact of bilingualism on executive functions and working memory in young adults. *PLoS One* **14**, e0206770 (2019).
21. G. D. Arizmendi *et al.*, Do bilingual children have an executive function advantage? Results from inhibition, shifting, and updating tasks. *Lang. Speech Hear. Serv. Sch.* **49**, 356–378 (2018).
22. A. S. Dick *et al.*, No evidence for a bilingual executive function advantage in the nationally representative ABCD study. *Nat. Hum. Behav.* **3**, 692–701 (2019).
23. M. Lehtonen *et al.*, Is bilingualism associated with enhanced executive functioning in adults? A meta-analytic review. *Psychol. Bull.* **144**, 394–425 (2018).
24. K. R. Paap, H. A. Johnson, O. Sawi, Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex* **69**, 265–278 (2015).
25. A. I. Ladas, D. J. Carroll, A. B. Vivas, Attentional processes in low-socioeconomic status bilingual children: Are they modulated by the amount of bilingual experience? *Child Dev.* **86**, 557–578 (2015).
26. E. S. Nichols, C. J. Wild, B. Stojanoski, M. E. Battista, A. M. Owen, Bilingualism affords no general cognitive advantages: A population study of executive function in 11,000 people. *Psychol. Sci.* **31**, 548–567 (2020).
27. K. R. Paap, Z. I. Greenberg, There is no coherent evidence for a bilingual advantage in executive processing. *Cogn. Psychol.* **66**, 232–258 (2013).
28. E. Antón, Y. Fernández García, M. Carreiras, J. A. Duñabeitia, Does bilingualism shape inhibitory control in the elderly? *J. Mem. Lang.* **90**, 147–160 (2016).
29. N. W. Kirk, L. Fiala, K. C. Scott-Brown, V. Kempe, No evidence for reduced Simon cost in elderly bilinguals and bidialectals. *J. Cogn. Psychol. (Hove)* **26**, 640–648 (2014).
30. V. DeLuca, J. Rothman, E. Bialystok, C. Pliatsikas, Duration and extent of bilingual experience modulate neurocognitive outcomes. *Neuroimage* **204**, 116222 (2020).
31. C. E. Snow, M. Hoefnagel-Hohle, The critical period for language acquisition: Evidence from second language learning. *Child Dev.* **49**, 1114–1128 (1978).
32. S. J. Blakemore, S. Choudhury, Development of the adolescent brain: Implications for executive function and social cognition. *J. Child Psychol. Psychiatry* **47**, 296–312 (2006).
33. S. M. Sawyer *et al.*, Adolescence: A foundation for future health. *Lancet* **379**, 1630–1640 (2012).
34. S. A. Everson-Rose, C. F. Mendes de Leon, J. L. Bienias, R. S. Wilson, D. A. Evans, Early life conditions and cognitive functioning in later life. *Am. J. Epidemiol.* **158**, 1083–1089 (2003).
35. V. Deluca, J. Rothman, C. Pliatsikas, Linguistic immersion and structural effects on the bilingual brain: A longitudinal study. *Biling. Lang. Cogn.* **22**, 1160–1175 (2019).
36. S. Hayakawa, V. Marian, Consequences of multilingualism for neural architecture. *Behav. Brain Funct.* **15**, 6 (2019).
37. T. M. Becker, C. S. Prat, A. Stocco, A network-level analysis of cognitive flexibility reveals a differential influence of the anterior cingulate cortex in bilinguals versus monolinguals. *Neuropsychologia* **85**, 62–73 (2016).
38. J. Gonzalez-Castillo *et al.*, Tracking ongoing cognition in individuals using brief, whole-brain functional connectivity patterns. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 8762–8767 (2015).
39. B. P. Rogers, V. L. Morgan, A. T. Newton, J. C. Gore, Assessing functional connectivity in the human brain by fMRI. *Magn. Reson. Imaging* **25**, 1347–1357 (2007).
40. E. S. Finn *et al.*, Functional connectome fingerprinting: Identifying individuals using patterns of brain connectivity. *Nat. Neurosci.* **18**, 1664–1671 (2015).
41. K. Yoo *et al.*, Multivariate approaches improve the reliability and validity of functional connectivity and prediction of individual behaviors. *Neuroimage* **197**, 212–223 (2019).
42. M. D. Rosenberg *et al.*, Functional connectivity predicts changes in attention observed across minutes, days, and months. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 3797–3807 (2020).
43. M. D. Rosenberg *et al.*, A neuromarker of sustained attention from whole-brain functional connectivity. *Nat. Neurosci.* **19**, 165–171 (2016).

44. K. Yoo *et al.*, Connectome-based predictive modeling of attention: Comparing different functional connectivity features and prediction methods across datasets. *Neuroimage* **167**, 11–22 (2018).
45. E. W. Avery *et al.*, Distributed patterns of functional connectivity predict working memory performance in novel healthy and memory-impaired individuals. *J. Cogn. Neurosci.* **32**, 241–255 (2020).
46. Q. Lin *et al.*, Resting-state functional connectivity predicts cognitive impairment related to Alzheimer's disease. *Front. Aging Neurosci.* **10**, 94 (2018).
47. D. Tomasi, N. D. Volkow, Network connectivity predicts language processing in healthy adults. *Hum. Brain Mapp.* **41**, 3696–3708 (2020).
48. H. Cai, J. Zhu, Y. Yu, Robust prediction of individual personality from brain functional connectome. *Soc. Cogn. Affect. Neurosci.* **15**, 359–369 (2020).
49. W. T. Hsu, M. D. Rosenberg, D. Scheinost, R. T. Constable, M. M. Chun, Resting-state functional connectivity predicts neuroticism and extraversion in novel individuals. *Soc. Cogn. Affect. Neurosci.* **13**, 224–232 (2018).
50. M. Luciana *et al.*, Adolescent neurocognitive development and impacts of substance use: Overview of the adolescent brain cognitive development (ABCD) baseline neurocognition battery. *Dev. Cogn. Neurosci.* **32**, 67–79 (2018).
51. P. M. J. Engel de Abreu, Working memory in multilingual children: Is there a bilingual effect? *Memory* **19**, 529–537 (2011).
52. J. Giovannoli, D. Martella, F. Federico, S. Pirchio, M. Casagrande, The impact of bilingualism on executive functions in children and adolescents: A systematic review based on the PRISMA method. *Front. Psychol.* **11**, 574789 (2020).
53. E. Antón *et al.*, Is there a bilingual advantage in the ANT task? Evidence from children. *Front. Psychol.* **5**, 398 (2014).
54. E. Blom, T. Boerma, E. Bosma, L. Cornips, E. Everaert, Cognitive advantages of bilingual children in different sociolinguistic contexts. *Front. Psychol.* **8**, 552 (2017).
55. J. Ross, A. Melinger, Bilingual advantage, bidialectal advantage or neither? Comparing performance across three tests of executive function in middle childhood. *Dev. Sci.* **20**, e12405 (2017).
56. M. I. Posner, Orienting of attention. *Q. J. Exp. Psychol.* **32**, 3–25 (1980).
57. E. Bialystok, The bilingual adaptation: How minds accommodate experience. *Psychol. Bull.* **143**, 233–262 (2017).
58. J. F. Kroll, E. Bialystok, Understanding the consequences of bilingualism for language processing and cognition. *J. Cogn. Psychol.* **25**, 497–514 (2013).
59. E. K. Miller, J. D. Cohen, An integrative theory of prefrontal cortex function. *Annu. Rev. Neurosci.* **24**, 167–202 (2001).
60. M. Bedny, A. Pascual-Leone, D. Dodell-Feder, E. Fedorenko, R. Saxe, Language processing in the occipital cortex of congenitally blind adults. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 4429–4434 (2011).
61. C. Pliatsikas, E. Moschopoulou, J. D. Saddy, The effects of bilingualism on the white matter structure of the brain. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 1334–1337 (2015).
62. S. G. Mohades *et al.*, Age of second language acquisition affects nonverbal conflict processing in children: An fMRI study. *Brain Behav.* **4**, 626–642 (2014).
63. X. Fan *et al.*, The differences in the whole-brain functional network between cantonese-mandarin bilinguals and mandarin monolinguals. *Brain Sci.* **11**, 310 (2021).
64. W. J. Chai, A. I. Abd Hamid, J. M. Abdullah, Working memory from the psychological and neurosciences perspectives: A review. *Front. Psychol.* **9**, 401 (2018).
65. S. J. G. Lewis, A. Dove, T. W. Robbins, R. A. Barker, A. M. Owen, Striatal contributions to working memory: A functional magnetic resonance imaging study in humans. *Eur. J. Neurosci.* **19**, 755–760 (2004).
66. A. B. Moore, Z. Li, C. E. Tyner, X. Hu, B. Crosson, Bilateral basal ganglia activity in verbal working memory. *Brain Lang.* **125**, 316–323 (2013).
67. J. G. Grundy, J. A. E. Anderson, E. Bialystok, Neural correlates of cognitive processing in monolinguals and bilinguals. *Ann. N. Y. Acad. Sci.* **1396**, 183–201 (2017).
68. H. Zhang *et al.*, Do intrinsic brain functional networks predict working memory from childhood to adulthood? *Hum. Brain Mapp.* **41**, 4574–4586 (2020).
69. M. D. Rosenberg *et al.*, Behavioral and neural signatures of working memory in childhood. *J. Neurosci.* **40**, 5090–5104 (2020).
70. M. Tamietto, B. de Gelder, Neural bases of the non-conscious perception of emotional signals. *Nat. Rev. Neurosci.* **11**, 697–709 (2010).
71. E. Leivada, M. Westergaard, J. A. Duñabeitia, J. Rothman, On the phantom-like appearance of bilingualism effects on neurocognition: (How) should we proceed? *Biling. Lang. Cogn.* **24**, 197–210 (2021).
72. V. DeLuca, J. Rothman, E. Bialystok, C. Pliatsikas, Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 7565–7574 (2019).
73. B. J. Casey *et al.*; ABCD Imaging Acquisition Workgroup, The Adolescent Brain Cognitive Development (ABCD) study: Imaging acquisition across 21 sites. *Dev. Cogn. Neurosci.* **32**, 43–54 (2018).
74. C. M. Hamilton *et al.*, The PhenX Toolkit: Get the most from your measures. *Am. J. Epidemiol.* **174**, 253–260 (2011).
75. M. Antoniou, S. M. Wright, Uncovering the mechanisms responsible for why language learning may promote healthy cognitive aging. *Front. Psychol.* **8**, 2217 (2017).
76. S. Knecht *et al.*, Handedness and hemispheric language dominance in healthy humans. *Brain* **123**, 2512–2518 (2000).
77. K. G. Noble, B. D. McCandliss, M. J. Farah, Socioeconomic gradients predict individual differences in neurocognitive abilities. *Dev. Sci.* **10**, 464–480 (2007).
78. B. A. Eriksen, C. W. Eriksen, Effects of noise letters upon the identification of a target letter in a nonsearch task. *Percept. Psychophys.* **16**, 143–149 (1974).
79. G. D. Logan, "On the ability to inhibit thought and action: A users guide to the stop-signal paradigm" in *Inhibitory Processes in Attention, Memory, and Language*, D. Dagenbach, T. H. Carr, Eds. (Academic Press, 1994), pp. 189–239.
80. W. K. Thompson *et al.*, The structure of cognition in 9 and 10 year-old children and associations with problem behaviors: Findings from the ABCD study's baseline neurocognitive battery. *Dev. Cogn. Neurosci.* **36**, 100606 (2019).
81. D. S. Tulsky *et al.*, NIH Toolbox Cognition Battery (NIHTB-CB): List sorting test to measure working memory. *J. Int. Neuropsychol. Soc.* **20**, 599–610 (2014).
82. P. J. Bauer *et al.*, III. NIH Toolbox Cognition Battery (CB): Measuring episodic memory. *Monogr. Soc. Res. Child Dev.* **78**, 34–48 (2013).
83. C. E. L. Stark, Y. Okado, Making memories without trying: Medial temporal lobe activity associated with incidental memory formation during recognition. *J. Neurosci.* **23**, 6748–6753 (2003).
84. T. E. Nichols, A. P. Holmes, Nonparametric permutation tests for functional neuroimaging: A primer with examples. *Hum. Brain Mapp.* **15**, 1–25 (2002).
85. D. J. Hagler, Jr *et al.*, Image processing and analysis methods for the Adolescent Brain Cognitive Development Study. *Neuroimage* **202**, 116091 (2019).
86. R. W. Cox, AFNI: Software for analysis and visualization of functional magnetic resonance neuroimages. *Comput. Biomed. Res.* **29**, 162–173 (1996).
87. X. Shen, F. Tokoglu, X. Papademetris, R. T. Constable, Groupwise whole-brain parcellation from resting-state fMRI data for network node identification. *Neuroimage* **82**, 403–415 (2013).
88. B. E. Boser, I. M. Guyon, V. N. Vapnik, "Training algorithm for optimal margin classifiers" in *Proceedings of the Fifth Annual ACM Workshop on Computational Learning Theory* (Association for Computing Machinery, 1992), pp. 144–152.
89. V. Vapnik, S. E. Golowich, A. Smola, "Support vector method for function approximation, regression estimation, and signal processing" in *Advances in Neural Information Processing Systems*, M. C. Mozer, M. I. Jordan, T. Petsche, Eds. (The MIT Press, 1997), pp. 281–287.
90. N. Thai-Nghe, Z. Gantner, L. Schmidt-Thieme, "Cost-sensitive learning methods for imbalanced data" in *Proceedings of the International Joint Conference on Neural Networks* (IEEE, 2010), pp. 1–8.
91. D. Bzdok, J. P. A. Ioannidis, Exploration, inference, and prediction in neuroscience and biomedicine. *Trends Neurosci.* **42**, 251–262 (2019).
92. X. Shen *et al.*, Using connectome-based predictive modeling to predict individual behavior from brain connectivity. *Nat. Protoc.* **12**, 506–518 (2017).