Mapping the unconscious maintenance of a lost first language

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Optimal periods during early development facilitate the formation of perceptual representations, laying the framework for future learning. A crucial question is whether such early representations are maintained in the brain over time without continued input. Using functional MRI, we show that internationally adopted (IA) children from China, exposed exclusively to French since adoption (mean age of adoption, 12.8 mo), maintained neural representations of their birth language despite functionally losing that language and having no conscious recollection of it. Their neural patterns during a Chinese lexical tone discrimination task matched those observed in Chinese/French bilinguals who have had continual exposure to Chinese since birth and differed from monolingual French speakers who had never been exposed to Chinese. They processed lexical tone as linguistically relevant, despite having no Chinese exposure for 12.6 y, on average, and no conscious recollection of that language. More specifically, IA participants recruited left superior temporal gyrus/planum temporale, matching the pattern observed in Chinese/French bilinguals. In contrast, French speakers who had never been exposed to Chinese did not recruit this region and instead activated right superior temporal gyrus. We show that neural representations are not overwritten and suggest a special status for language input obtained during the first year of development.

brain | fMRI | language | neural representations | early age effects

The brain has been shown to exhibit remarkable plasticity, across perceptual domains, allowing it to learn from and adapt to changing input from the environment (1). Although we know that input from the outside world can shape and influence the brain, a more contentious issue is whether such changes are long-lasting without continued input. On the one hand, there is a long-standing argument in the domain of language that, at least up until adolescence, circuits subserving language remain plastic such that early developed neural representations can be overwritten if exposure to that language is not maintained (2, 3). On the other hand, research in the field of learning and memory would argue that once a memory trace is established it is maintained indefinitely and any subsequent forgetting is actually a problem of retrieval (4). In fact, increasingly, evidence from language research supports this latter hypothesis (5–8), at least at the behavioral level. The present study addressed this issue in a unique population of language learners, internationally adopted (IA) children, and provides, to our knowledge, the first neural evidence that early formed language representations are maintained in the brain even if exposure to that language is discontinued.

Brain organization is particularly sensitive to external input during critical or optimal periods in early development (8). Optimal periods are defined as windows of heightened plasticity, during which environmental input is highly influential, followed by a reduction in plasticity as perceptual representations become established and the effect of environmental input is greatly reduced (9). For example, the visual cortex must receive input from both eyes during early development for binocular vision to develop normally (10), and songbirds establish their adult song based on input received during an early critical period (11). If input is received outside these periods, then normal vision is never achieved, and an aberrant song develops. In the language domain, the first year of life appears to be an optimal period for the development of sound categories in the native language, achieved through a process of perceptual attunement (12, 13). Infants begin life with an ability to discriminate sound categories present across the world's languages. However, over time and with exposure to a specific language, perceptual sensitivity to native-language sound categories is enhanced, whereas sensitivity to nonnative sound categories is reduced, allowing for specialization in one's native language (13). The phonological categories formed during this time provide the organizational foundation necessary to support increasingly higher levels of language development, such as word learning, grammar, and reading (8). Although much research has sought to understand the formation of these early representations, their maintenance beyond this initial formation is not well understood.

A unique body of research examining the longevity of early representations of language comes from adults' responses to a language they heard as children but did not maintain—namely, IA individuals who experienced a language switch at adoption. Pallier et al. (2) reported that French-speaking IA adults, who had heard Korean as children, showed similar brain activation when listening to Korean sentences as French monolinguals without this early experience. Sentences in another unfamiliar language also activated similar regions in these groups. Behaviorally, Ventureyra (14) found that Korean adoptees performed similarly to French monolingual speakers on a Korean discrimination task, even after

Significance

Using functional MRI we examined the unconscious influence of early experience on later brain outcomes. Internationally adopted (IA) children (aged 9–17 years), who were completely separated from their birth language (Chinese) at 12.8 mo of age, on average, displayed brain activation to Chinese linguistic elements that precisely matched that of native Chinese speakers, despite the fact that IA children had no subsequent exposure to Chinese and no conscious recollection of that language. Importantly, activation differed from monolingual French speakers with no Chinese exposure, despite all participants hearing identical acoustic stimuli. The similarity between adoptees and Chinese speakers clearly illustrates that early acquired information is maintained in the brain and that early experiences unconsciously influence neural processing for years, if not indefinitely.

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brief reexposure to their birth language as adults. These studies argue against the maintenance of early formed language representations. However, the sensitivity of these tasks to elicit such representations has been called into question. For example, the tasks may have been sensitive to linguistic elements that were not actually developed before adoption. Specifically, sentence-level processing includes more complex grammatical elements that would likely not have been acquired during the first year. Moreover, Pallier did not compare IA participants to native Korean speakers, and thus, native-like neural patterns could not be examined. Finally, the type of reexposure examined by Ventureyra may have been insufficient to elicit strong behavioral effects (6). In fact, reexposed IA participants actually showed significant advantages on the easiest contrast examined—a tense-aspirated contrast that is phonemic in Korean (14). Given these adoptees' relatively low amount of reexposure to Korean, this is noteworthy, as it is possible that more, or more structured, Korean exposure may have yielded stronger effects.

Support for the retention of early acquired language representations comes from behavioral advantages observed on tasks in a language that participants were exposed to as children but discontinued as a result of either immigration or adoption, compared with participants with no exposure to that language. For example, participants with discontinued exposure have been found to exhibit better performance on contrast discrimination (8), understanding of phonological rules, production of more native-like voice-onset times and accents (5), and enhanced consonant perception and production (15). Gains have also been observed in response to training of a discontinued first language, leading to better performance on contrast discrimination tasks (6, 7). Similar benefits are not observed for comparison groups without early exposure to the language tested. Although studies such as these appear to demonstrate the maintenance of early established representations in the face of discontinued language exposure, they have been criticized because of the possibility that the discontinued language may have been present to some degree within their participants' environment postimmigration, as in the case of children who moved with their families. Even in cases examining IA participants, who were completely cut off from exposure to their birth language following adoption, results are subtle, likely owing to small and heterogeneous samples, as well as limitations of using behavioral measures alone.

In the present study, we addressed these issues, improving on previous methods by using a sensitive task with selective control groups to determine whether or not neural representations of a "lost" language are maintained. We examined brain activation using functional magnetic resonance imaging (fMRI) in French-speaking IA children from China who had early but discontinued exposure to Chinese, compared with groups either with Chinese exposure since birth (Chinese/French bilinguals) or without exposure to this language (French monolinguals). Examining this question neurocognitively allowed us to examine effects that may not be observable using behavioral assessments alone, and including native speakers of IA participants' birth language allowed us to establish the activation patterns associated with continuous exposure to that language from birth. We also improved on the assessment methods of previous research with IA participants by using a linguistic element known to be acquired early, but that is no longer present in IA children's language environment, specifically Chinese lexical tones. In tonal languages, such as Mandarin and Cantonese (but not French), lexical tones are phonemic such that the same syllable has a different meaning depending on the tone applied. For example, the Mandarin word "ma" can mean mother, hemp, horse, or scold, depending on its tone [i.e., variations in fundamental frequency (f0) level and/or contour within the syllable] (16). Because lexical tone is not present in IA participants' post-adoption language environment, any native-like activation to this linguistic element must be due to the maintenance of early established representations.

Two additional characteristics of lexical tone make it a particularly sensitive tool for examining the longevity of early formed representations. First, infants create sound categories for native-language tones early in development through a process of perceptual attunement (17, 18) that parallels that observed for other linguistic elements such as vowels and consonants (19, 20). Infants learning Chinese show preferences for the tonal contrasts of their native language by about 4–5 mo of age (18), well in advance of the age of adoption (AoA) of participants in the present study. In addition, learning to perceive these tonal contrasts as distinct linguistic categories is difficult for adults without prior experience with tone languages (21). This suggests that receiving early input in this domain is crucial for later discrimination of tonal categories.

Second, brain activity to tone information has been shown to differ between individuals with and without experience with tonal languages, allowing for predictions based on linguistic experience. For speakers of nontonal languages, right hemisphere frontal and temporal regions specialized for processing acoustic frequency information, such as nonphonemically relevant prosody and intonation, are activated when listening to tones (22, 23). In contrast, speakers of tonal languages recruit relevant left frontal, temporal, and parietal-occipital language regions (24); left frontal operculum (25); and the left premotor cortex, pars opercularis, and pars triangularis (26) when processing lexical tone in various experimental paradigms. This effect is language specific, as native-language tones activate left hemisphere language regions, particularly the left superior temporal gyrus (STG) and planum temporale (PT), more strongly than do nonnative tones (27). This left hemisphere recruitment, not observed in speakers of nontonal languages, indicates the incorporation of learned top–down operations on the processing of acoustic signals. This effect is specific to lexical tone, rather than an increased sensitivity to pitch information in general as, even within tonal language speakers, nonphonemically relevant global intonation is processed by right hemisphere regions, whereas similar information attached to tonal contrasts is processed in left frontal and temporal regions (28). This clearly illustrates the role of experience, as similar acoustic elements were processed differently depending on their learned linguistic relevance. Thus, the IA participants in the present study would be highly unlikely to recruit this region if the effects of their early experience were not maintained.

By using brain imaging to examine activation to an early acquired linguistic element in three carefully selected groups, we were able to show, to our knowledge, the first evidence at the neural level for the maintenance of an essential feature of a lost first language.

Results

To test whether early established neural representations for language persist despite discontinuation of that language, we scanned three groups of 9–17-y-old participants using fMRI. Participants (Table S1) were (*i*) IA children adopted into French-speaking families (mean AoA, 12.6 mo; range, 6–25 mo) who now speak only French ($n = 21$); (*ii*) children who were exposed to Chinese as a first language, began learning French as a second language (mean age of French onset, 16.9 mo; range, 0–36 mo) and are now Chinese–French bilinguals ($n = 12$); and (*iii*) French monolingual children who had never been exposed to Chinese ($n = 11$) (see *SI Methods* for details on language background). To control for several factors, including current age and age of French onset (in the case of the IA children, this directly corresponds to AoA; in the case of bilingual children, this corresponds to the age they were first exposed to French, as specified by their parents), group patterns and between-group

comparisons were conducted on matched subgroups ($n = 10$ per group). However, these comparisons were also conducted at the full group level (*SI Methods*). Within-group regression analyses, conducted on the full group of IA participants ($n = 21$), examined whether length of exposure to Chinese or length of time since exposure to Chinese affected their recruitment of brain regions during the Chinese tone discrimination task.

While in the scanner, participants heard pairs of three syllable phrases that were either monosyllabic Chinese pseudowords (that included lexical tone) or nonspeech hummed versions of the same syllables containing tone information but no actual words (28). Comparing lexical tone and hums allowed us to isolate linguistically relevant activation. Sentences were either identical or the final syllable varied on tonal information only. While in the scanner, participants were instructed to respond with a button press to indicate if the final syllables in each pair were the same or different. Accuracy and reaction time were collected to assess task performance.

Behavioral Analyses. All participants performed the tonal discrimination task with high accuracy in both the lexical tone (mean bilingual, 92.2%; mean monolingual, 86.0%, mean IA, 86.3%) and the hum conditions (mean bilingual, 92.2%; mean monolingual, 85.2%; mean IA, 88.4%). There were no significant differences in accuracy between any of the groups in the lexical tone, $F(2, 27) = 1.13$, $P = 0.337$, or the hum, $F(2, 27) = 1.79$, $P = 0.185$, conditions. Participants also responded with similar reaction times in both the lexical tone (mean bilingual, 334.4 ms; mean monolingual, 338.1 ms; mean IA, 212.0 ms) and the hum (mean bilingual, 319.9 ms; mean monolingual, 306.3 ms; mean IA, 224.1 ms) conditions. There were no statistically significant differences in reaction time for either the lexical tone, $F(2, 27) = 2.76$, $P = 0.081$, or the hum, $F(2, 27) = 1.98$, $P = 0.157$, conditions. Accuracy and reaction time results are discussed further in *SI Methods*.

Peak Activation by Group. We began our fMRI analysis by examining general patterns in activation observed for each group: bilinguals, monolinguals, and IA participants. Brain activation to hummed stimuli was examined against a silent baseline to ensure that the groups did not differ in activation to this control condition. Groups did not differ in this comparison (Fig. S1). Crucial to the main research question, brain activation specific to the processing of lexical tone was obtained for each group as a subtraction between the lexical tone and the hum conditions. In this way, we removed activation elicited by factors such as decision-making, categorization, and working memory. A whole brain threshold of $t = 5.5$ was applied to determine significant peak activation within a whole-brain, voxel-wise analysis. Results are presented for each group next (Fig. 1 and Table S2).

Chinese–French bilinguals: Lexical tone minus hum condition. On the lexical tone task, for the Chinese–French bilinguals, the largest peaks were in the left hemisphere, with a strong peak in the left anterior STG/PT and a lower magnitude peak extending to the posterior STG/supramarginal gyrus. In the right hemisphere, one peak was present in the anterior STG (Fig. 1 and Table S2).

Monolingual French: Lexical tone minus hum condition. Monolingual French participants activated the right hemisphere only. Activity was observed in the right posterior STG and supramarginal gyrus, as well as in the right occipital cortex and hippocampus (Fig. 1 and Table S2).

IAs: Lexical tone minus hum condition. IA participants, like the bilinguals, activated mainly the left hemisphere. Like the Chinese–French bilinguals, the largest peak occurred in the left anterior STG/ PT, and activity extended to the posterior STG. In the right hemisphere, one peak was present in the anterior STG (Fig. 1 and Table S2).

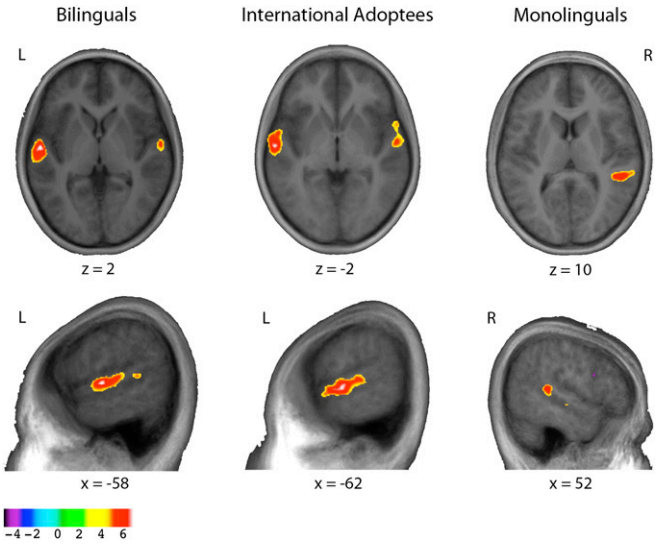


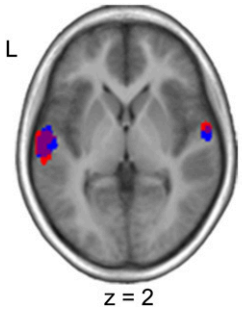
Fig. 1. *t* maps showing activation patterns for bilinguals ($n = 10$), IAs ($n = 10$), and monolinguals ($n = 10$) in a subtraction of the lexical tone minus hum conditions overlaid on the average anatomical t1 images of each group. Slices are shown in the axial (*Top*) and sagittal (*Bottom*) planes and are taken from the coordinate displaying the highest *t* value for each group in this subtraction. Note the strikingly similar patterns of activation for the IA and Chinese group and the contrasting pattern for the monolingual French group, supporting the notion of neural traces of a lost first language despite discontinued use.

Results from the analyses of each group revealed that the bilingual and IA participants displayed strikingly similar activation when discriminating/hearing lexical tones. Both groups activated several regions within the left temporal cortex. These regions have consistently been recruited in previous research on tonal processing and are thought to be important for the processing of tone in speakers of tonal languages (24, 25). Of particular interest is the strong activation in the left PT, previously shown to be modulated by familiarity with a tonal language (27). In contrast, the monolinguals recruited the right posterior STG, a region not observed in the other groups and one that is consistent with the nonlinguistic processing of a complex acoustic signal (23). Results presented here are for carefully matched subgroups, however full group patterns were virtually identical (Fig. S2 and Table S3).

Conjunction Analysis. To confirm that the bilinguals and IA participants activated the same regions when processing lexical tone, a conjunction analysis was performed. This analysis directly compares groups to identify regions of joint activation. Results showed that the IA and bilingual groups activated the same region in the left STG/PT. Within this cluster, two peaks were significant and a third approached statistical significance (Fig. 2). Neither the monolingual and bilingual groups nor the monolingual and IA groups shared regions of activation.

Taken together with the individual group results, the conjunction analyses further demonstrate the striking similarity in activation between the IA and bilingual participants, as well as the distinct response pattern observed for the French monolinguals who had never been exposed to Chinese.

Regression Analysis. To identify the extent to which changes in blood-oxygen–level dependent (BOLD) signal were related to amount of exposure to Chinese and/or length of time since exposure to Chinese, a whole-brain, voxel-wise linear regression was performed within the full IA group ($n = 21$). Predictor variables were AoA (higher AoA means more exposure to Chinese),



Conjunction analysis – overlapping activation between IA and Chinese-French bilinguals

Region	x	y	z	*p*
Left PT	-62	-12	2	0.004
	-64	-14	2	0.01
	-60	-22	4	0.081

IA = Red; Bilingual = Blue

Fig. 2. (*Left*) Graphical representation of conjunction analysis demonstrating overlapping activation across bilingual (n = 10) and IA (n = 10) groups in the lexical tone minus hum subtraction. Activation for the IA group is displayed in red, and activation for the bilingual group is displayed in blue. Regions of overlap are displayed in purple. Conjunction in the right hemisphere did not reach significance. (*Right*) Coordinates of peaks within the significantly overlapping cluster that reached or approached statistical significance. Note the virtual overlap between the two groups.

current age, and time since exposure to Chinese (current age minus AoA). Each factor was included in a separate analysis for the lexical tone condition against the hum condition. Because activation in the left STG was predicted based on our previous analyses, a cluster threshold of 4.3 was applied. This corresponded to the significant cluster volume from this regression analysis. One significant cluster in the left STG was positively associated with AoA. Within this cluster, a significant peak was present in the left PT, indicating greater activation in this region for those IA participants who had more exposure to Chinese before adoption (Fig. 3). Current age and time since Chinese exposure were not significantly associated with activity in any brain region.

It is striking that this analysis again revealed significant activation in the left PT, the same region reported in the individual group analysis as well as in the conjunction analysis. That this region, which was also activated by the bilingual group, is affected by AoA suggests that more exposure to Chinese during early development leads to stronger representations for lexical tone. The fact that age at testing and length of time since adoption were not associated with activity in this or any other region suggests that, once established, these early formed representations persist. That is, they do not degrade over time as a result of discontinued input. Results were not driven by differences in task performance (*SI Methods*).

Discussion

By examining brain activation to tonal contrasts in IA children from China compared with carefully selected controls with or without previous exposure to Chinese, we demonstrated neural evidence for the maintenance of a lost first language even after several years without exposure to or use of that language. When processing lexical tone, both the IA children and the Chinese–French bilinguals recruited left temporal regions, consistent with the idea that top–down processing of learned linguistic categories was applied when performing this task. In contrast, the French monolingual children did not recruit these left hemisphere regions but instead recruited right temporal regions implicated in the acoustic processing of a complex, but nonlinguistic, auditory signal.

Both the IA and bilingual participants activated the left temporal lobe from the posterior to anterior STG, exhibiting significant overlap in the left PT. This is consistent with previous research showing that speakers of tonal languages recruit left hemisphere language regions for the processing of lexical tone (24–26, 28). The left STG in general has been implicated in the detection of phonological, as opposed to acoustic, change (29), and the left anterior STG in particular is activated following extensive training on nonnative speech contrasts (30). It is thought that increasingly complex processing of an acoustic signal, via application of learned representations, is possible through posterior to anterior analysis progressing along the ventral stream in the left STG (31, 32). Thus, activation extending from the posterior to anterior STG in both the IA participants and the Chinese–French bilinguals supports the argument that these stimuli are linguistically relevant for both of these groups. That is to say, top–down application of stored representations allowed the tonal contrasts to be processed by these groups in an increasingly complex and hierarchical manner along this stream in a way that was not possible for the French monolinguals who did not possess these stored representations.

That the left PT in particular was strongly activated and convergent across these two groups is consistent with findings that this region is activated in response to tones (31), and more strongly activated in response to native-language tones in particular (27). Activity in this region has also been observed in native signers (33), as well as in trained musicians (34), indicating the significant influence of learning and experience on this region (27). Consistent with this interpretation is the hypothesis that the PT acts as a "computational hub," matching incoming complex sounds with previously experienced stored representations (35). This hypothesis not only emphasizes the relationship of PT with learned linguistic relevance but also indicates that this previously stored information can be applied even during early stages of acoustic processing (23). This is evident in the present finding that Chinese–French bilinguals recruit this region when processing lexical tone. That the IA participants also recruited this region despite not currently speaking nor having had any exposure to Chinese for 12.6 y on average provides evidence for the neural maintenance of early learned representations over time.

The finding that the AoA of the IA children was positively related to left PT activation is also striking. All of the IA children showed activation in this region to some extent that was greater in response to lexical tone than to hums. However, the IA children who were adopted at later ages showed greater activation than those who were adopted earlier. This might indicate that, even though children as young as 6 mo of age have already established native-language representations, these become increasingly developed with increased experience. The IA children adopted at the latest ages, who thus had the most exposure to Chinese, were likely able to establish stronger representations for lexical tone. What is interesting, however, is that the IA children showed remarkably similar activation to the bilingual children, despite discontinued exposure to Chinese at an early

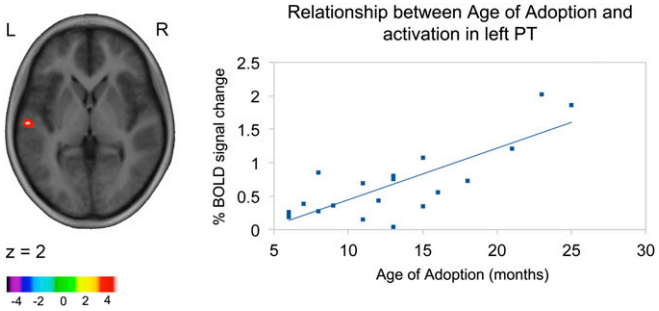


Fig. 3. Whole-brain regression analysis examining whether AoA was related to activity in any brain region in the lexical tone minus hum subtraction for IAs (n = 21). The t map (*Left*) and scatterplot (*Right*) show the cluster in the left STG/PT whose peak coordinate showed greater activation in IA participants who were adopted at later ages, and thus experienced more exposure to Chinese.

age. This suggests that once these representations are acquired (i.e., during an early optimal period), they may remain relatively stable and are not affected by continued exposure beyond a certain limit. Also important is the finding that no relationship existed between the IA children's current age or the amount of time since their exposure to Chinese, further suggesting that early formed representations are long lasting, regardless of how much time has passed.

Because the IA children had not been exposed to Chinese since adoption (12.8 mo of age, on average), it is necessarily the case that any neural representations that they recruited for processing their lost first language must have been acquired during early language development, before adoption. This suggests that information obtained during what some have argued is an optimal period for phonological development (12) may have special relevance that persists even without continued input. That is, if infants develop neural representations for native-language sounds during an early optimal period, these may remain with them indefinitely, despite any subsequent learning of other languages. This is consistent with human and animal research demonstrating that newly learned information does not replace circuits established by preexisting information, even if this initial information becomes difficult to access (36). The function of maintaining these representations is clear in individuals who continue to speak their first language, as these form the foundation of subsequent language learning (8). Maintaining this information without continued input may be a side effect of this property of neural circuitry (i.e., to not be overwritten), and may also allow for faster or more complete relearning if the original language were to be reinstated (37), as has been observed in several behavioral studies (5–8, 15). However, an open question remains as to whether and how this initial organization might influence the acquisition and processing of any subsequently learned languages. It may further explain some of the differences observed between IA children and monolingual native-language speakers in language and verbal short-term memory, especially phonological short-term memory, that have been found to persist for several years postadoption (38, 39).

The brain exhibits tremendous plasticity and a pronounced ability to adapt to its environment. Part of its ability to adapt and learn, however, may involve retaining information potentially valuable for later use. Alternatively, it may be the case that the benefits of establishing and maintaining representations that help the learner make sense of complex sounds in their native language during infancy outweigh the costs of not maintaining those representations and instead having to continually reinterpret which sounds are relevant and why. In any case, the present results support previous research demonstrating behavioral remnants of a lost first language (5–8, 15) and provide, to our knowledge, the first neural evidence that early formed language representations are maintained in the brain even if exposure to that language is discontinued.

Methods

Participants. Participants (Table S1) included three groups of females (n = 48), as adoptees from China are typically female (39, 40) (see *SI Methods* for details on Chinese adoption): (*i*) IA children adopted into French-speaking families before age 3, who now speak only French (n = 23; mean age, 13.7 y; mean AoA, 12.6 mo); (*ii*) children who learned Chinese from birth, began learning French as a second language by age 3, and are now Chinese–French bilinguals (n = 12; mean age, 13.0 y; mean age of French onset, 17 mo); and (*iii*) French monolingual children who had never been exposed to Chinese (n = 13; mean age, 13.7 y). Two participants each were excluded from the IA and monolingual groups (*SI Methods*). To control for several factors, as well as to ensure equal sample sizes across groups, group patterns and between-group comparisons were conducted on matched subgroups (n = 10 per group; see Table S1 and *SI Methods* for details). However, analyses conducted on the larger group of adoptees showed a virtually identical pattern (Fig. S2 and Table S3). Matched groups were IA children (mean age at testing, 13.5 y; mean AoA, 12.8 mo), Chinese–French bilinguals (mean age at testing, 13.5 y; mean age of French onset, 16.9 mo), and French monolinguals (mean age at testing, 13.3 y). Groups did not differ in terms of current age, $F(2,27) = 0.022$, $P = 0.979$, or age of French onset, $t(18) = -0.991$, $P = 0.335$. Within-group regression analyses were conducted on the full group of IA participants (n = 21). Sample sizes are comparable to those used in previous studies using similar paradigms (28). Participants were all healthy and right-handed and had normal hearing. Informed consent was obtained from caregivers, and assent obtained from all participants, before beginning the experiment. The study received research ethics board approval at the local institution (Montreal Neurological Institute).

Behavioral Assessment. Participants' parents completed two questionnaires to obtain information regarding children's early developmental history, as well as their language environments and background (*SI Methods*). Participants completed standardized language and general cognitive measures (*SI Methods*); the Wechsler block design subtest, a visuo-spatial construction task, was included to determine the extent to which any differences found between the groups of children were general or language-specific.

Stimuli and Procedure. The stimuli consisted of 56 syntactically acceptable sentence pairs composed of three monosyllabic pseudowords (e.g., da^1 shao^2 fa^1), as well as an equal number of comparable "hummed" sentence pairs, derived from resynthesized speech that contained identical duration, fundamental frequency, and intensity characteristics, but excluded vowel and consonant information. Thus, tonal information was retained in the hummed stimuli while eliminating linguistic context. Each sentence was constructed of three syllables to control for length effects. We used uninterpretable strings of pseudowords to minimize lexico-semantic effects, particularly because it is unlikely that the IA participants would have retained semantic information pertaining to Chinese words. Stimuli were derived from those used by Gandour and coworkers (28) and were recombined for the purposes of the present study. All stimuli were recorded by an adult male native speaker of Mandarin. The final syllable of each sentence contained tonal information from tones 1 (high-level), 2 (rising—comparable to Cantonese 2, high-rising), and 3 (dipping—comparable to Cantonese 5, low-rising) (41). These tones were chosen because of their high comparability across Mandarin and Cantonese, as well as several other Chinese dialects. Because both the Chinese–French bilinguals and the IA participants were exposed to Mandarin, Cantonese, or both, the overlap in tonal categories ensured that the information they heard would have been linguistically relevant. Stimuli were digitally edited to have equal maximum energy levels in dB sound pressure level (SPL) and were 16-bit digital sound files sampled at 44.1 kHz.

During scanning, participants heard pairs of three-syllable sentences constructed of monosyllabic pseudowords or nonspeech hummed versions of the pseudoword sentences containing tone information but no actual words (28). Sentences were either identical or the final syllable varied on tonal information only. Participants responded with a button press to indicate if the final syllable was the same or different (*SI Methods*). Accuracy and reaction time (measured from the offset of the final sentence) were collected to measure task performance. Before scanning, participants were trained on the task until reaching at least 80% accuracy to ensure that any differences observed could not be attributed to differences in performance.

fMRI Data Acquisition and Analysis. Image acquisition was performed on a 3T Siemens Trio scanner at the Montréal Neurological Institute. A global anatomical 3D T1-weighted, magnetization-prepared rapid gradient-echo (MPRAGE) scan was obtained for each participant, and motion correction was administered online using 3-D Prospective Acquisition Correction (42). fMRIstat software was used to perform a whole-brain, voxel-wise statistical analysis (43) (*SI Methods*). Subtractions examined were the lexical tone condition minus silence (baseline), lexical tone minus nonspeech hums, and nonspeech hums minus silence. A random effects analysis determined group-level statistical significance. Threshold significance was established as t = 5.50 for the whole-brain activation peaks and t = 4.30 for activation peaks within clusters. A conjunction analysis (44) determined regions of common activation between the bilingual and monolingual groups. Whole-brain, voxel-wise linear regressions were performed within the lexical tone minus nonspeech hum subtraction to determine whether BOLD signal changes within the IA group were modulated by individual differences in language experience.

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