

Bilingual infants control their languages as they listen

Krista Byers-Heinlein^{a,1}, Elizabeth Morin-Lessard^a, and Casey Lew-Williams^b

^aDepartment of Psychology, Concordia University, Montreal, QC, Canada H4B 1R6; and ^bDepartment of Psychology, Princeton University, Princeton, NJ 08544

Edited by Susan A. Gelman, University of Michigan, Ann Arbor, MI, and approved July 7, 2017 (received for review February 24, 2017)

Infants growing up in bilingual homes learn two languages simultaneously without apparent confusion or delay. However, the mechanisms that support this remarkable achievement remain unclear. Here, we demonstrate that infants use language-control mechanisms to preferentially activate the currently heard language during listening. In a naturalistic eye-tracking procedure, bilingual infants were more accurate at recognizing objects labeled in same-language sentences ("Find the dog!") than in switched-language sentences ("Find the chien!"). Measurements of infants' pupil size over time indicated that this resulted from increased cognitive load during language switches. However, language switches did not always engender processing difficulties: the switch cost was reduced or eliminated when the switch was from the nondominant to the dominant language, and when it crossed a sentence boundary. Adults showed the same patterns of performance as infants, even though target words were simple and highly familiar. Our results provide striking evidence from infancy to adulthood that bilinguals monitor their languages for efficient comprehension. Everyday practice controlling two languages during listening is likely to explain previously observed bilingual cognitive advantages across the lifespan.

bilingualism | infancy | code switching | language control | language processing

Bilingual infants have twice as much language to learn as monolinguals, yet their languages do not develop half as fast. These infants learn sounds (1) and words (2) in both languages with notably little difficulty, and achieve language milestones on largely the same schedule as monolinguals (3).

To effectively learn two languages, bilingual infants must separate and manage their languages during acquisition (4, 5). Within the first year of life, bilinguals discriminate their languages using both auditory (6–8) and visual cues (9). At age 2–3 y, toddlers show a neural response to a language change (10). Sensitivity to language-specific perceptual differences might help infants to begin separating and constructing distinct representations of each language (4, 11, 12). Indeed, evidence from artificial language learning suggests that bilingual infants are better able than monolingual infants to find structure in multiple streams of sounds and syllables (13, 14). However, little is known about when and how bilinguals represent their languages in a differentiated fashion. Existing language production studies suggest that children older than 2 y of age can match the language used by a conversational partner (15, 16), but the nature of how younger infants manage two languages during processing is currently unexplored.

In adults, language-control mechanisms enable bilinguals to produce the intended language. Experimental evidence for language control comes from studies showing that bilinguals are slower when they must switch from speaking one language to speaking the other (17, 18). This switch cost arises because bilinguals implicitly monitor and control the language currently being spoken by inhibiting the unintended language (19) or enhancing activation of the intended language (20), particularly when they are in a monolingual language mode (21). The double-edged sword of language control helps speakers produce words in the intended language, but results in a processing cost when switching between languages.

Although this type of language control has been extensively studied in adult language production, there has been little research

on comprehension, particularly with younger learners. However, language control during comprehension could be important for supporting early bilingual language acquisition. Although monolingual infants as young as 6 mo can comprehend some words (22), early comprehension is relatively slow, gradually gaining speed over the second year of life (23). Everyday speech unfolds quickly and in real time, and rapid recognition of one word is important for understanding the words that follow. Children with more efficient language processing abilities show greater gains in later language skills (24, 25), demonstrating the cascading benefits of efficient word comprehension.

In bilingual contexts, a word in one language is most often followed by another word in the same language, because language switches are rarer than sequences of words in a single language (26, 27). Bilinguals could more efficiently process upcoming words by preferentially activating the currently spoken language. At the same time, just like in the domain of language production, this type of language-control mechanism would slow processing during language switches. Limited evidence for language control in bilingual adults during listening comes from two studies examining language switches in highly restricted contexts: for example, deciding if spoken numbers are even or odd (28, 29). However, bilinguals' use of language control during comprehension remains poorly understood in adulthood, and untested in infancy.

Our study investigated the nature of bilinguals' language monitoring and control abilities across the lifespan. We designed an auditory language-switching task that simulates real-world language comprehension and places minimal additional cognitive demands on infants and adults. In a simplified visual world paradigm, bilingual infants (Exp. 1) and adults (Exp. 2) saw pairs of familiar pictures (e.g., a dog and a book), and heard either a same-language ("Look! Find the dog!") or a switched-language sentence ("Look! Find the *chien!*") naming one of the objects. Whereas Exps. 1 and 2 used intrasentential language switches (switches that occurred within a single sentence), Exp. 3 used intersentential language switches (language switches that crossed a sentence boundary; "That one looks fun! *Le chien!*"). Both

Significance

Bilingual infants must manage two languages in a single developing mind. However, the mechanisms that enable young bilinguals to manage their languages over the course of learning remain unclear. Here, we demonstrate that bilingual infants monitor and control their languages during real-time language listening, and do so similarly to bilingual adults. This ability could help bilinguals' language learning to keep pace with that of their monolingual peers, and may underpin the cognitive advantages enjoyed by bilinguals in both infancy and adulthood.

Author contributions: K.B.-H. and C.L.-W. designed research; E.M.-L. performed research; K.B.-H. and E.M.-L. analyzed data; and K.B.-H., E.M.-L., and C.L.-W. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: The experimental stimuli and data reported in this paper have been deposited in the Open Science Framework, <https://osf.io/htrn9j/>.

¹To whom correspondence should be addressed. Email: k.byers@concordia.ca.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1703220114/-DCSupplemental.

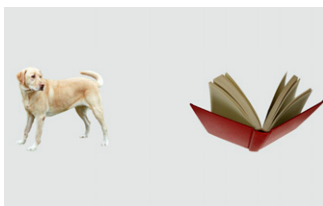
Sample auditory stimuli			Sample visual stimulus
Same-language		Switched-language	
Exps. 1 & 2			
English Block	Look! Find the dog!	Look! Find the <i>chien</i> !	
French Block	Regarde! Trouve le chien!	Regarde! Trouve le <i>dog</i> !	
Exp. 3			
English Block	That one looks fun! The dog!	That one looks fun! <i>Le chien</i> !	
French Block	Celui-là a l'air amusant! Le chien!	Celui-là a l'air amusant! <i>The dog</i> !	

Fig. 1. Sample auditory and visual stimuli used for same-language and switched-language trials, in English and French blocks. Auditory stimuli were produced by a balanced English–French bilingual female in an infant-directed manner. Target nouns were spliced into carrier phrases preserving coarticulatory cues, such that an identical token of each noun (Exps. 1 and 2) or determiner–noun pair (Exp. 3) was presented on same-language and switched-language trials. Switched words are shown in italics. Infants were randomly assigned to a block that was in either their dominant or nondominant language. Adults participated in both blocks.

types of language switching (also called code switching) are regularly heard by infants (30) and adults (31) living in bilingual communities. Note that the experimental paradigm was identical for both infants and adults; both groups looked at two pictures and listened to simple sentences, which ensured that the task was comparably natural for both groups. We hypothesized that bilinguals monitor and control their languages during everyday language listening, and that this engenders greater processing difficulty and higher cognitive load when hearing a language switch. Alternatively, bilinguals may be unable to deactivate the irrelevant language during listening (32), in which case they would show no detectable processing differences when encountering a language switch.

We used two eye-tracking measures to assess real-time processing and cognitive load. First, we examined participants' fixation to the target object in the moments after they heard the object label. A processing cost would be evidenced by less looking to the target object on switched-language trials than on same-language trials. Second, we measured pupil dilation concurrently with eye gaze. Pupil diameter is an involuntary response that varies not only with changes in luminance, but also with processing effort, making it a marker of cognitive load (33, 34). We expected that language switches would increase cognitive load, such that participants would have larger pupils after hearing a switched-language word than a same-language word. Our results reveal convergent evidence across both measures that bilingual infants and adults engage language-control mechanisms during listening.

Exp. 1: Infants

Participants were 20-mo-old English–French simultaneous bilingual infants ($n = 24$). We established infants' dominant (L1) and nondominant (L2) languages via parental report of the most-heard and least-heard language. Each infant saw one block of 18 trials. Each block was defined by the use of sentence frames presented in a consistent language, either in participants' dominant or nondominant language (English: "Look! Find the..."; French: "Regarde! Trouve le/la..."). Within each block, there were two trial types that varied the language of the final noun: same-language (six trials per block) and switched-language trials (six trials per block). An additional six same-language filler trials (not analyzed) were included in each block to decrease the frequency of language switching. The language switch occurred between the determiner and the noun (i.e., "the *chien*" or "le dog"), which is a common switch location for bilingual speakers of French (35, 36). Target nouns were chosen to be highly frequent and understood by infants of this age. See Fig. 1 for sample stimuli. Because infants have limited attention spans, they participated in only one block, randomly assigned to be in their dominant or nondominant language. An eye tracker measured the direction of participants' eye gaze and the diameter of their pupils.

As an index of processing, we examined participants' accuracy in looking to the target picture during a time window of 360–2,000 ms after the target noun onset. This was operationalized as the proportion of time infants looked at the target picture relative to the total time they looked at either picture. Means for each group are displayed in Fig. 2. On average, infants looked significantly more to the target on same-language trials [$\text{mean}_{\text{same}} = 0.60$ ($\text{SD} = 0.13$)] than on switched-language trials [$\text{mean}_{\text{switched}} = 0.51$ (0.12); $t(23) = 2.72$, $P = 0.012$, $d_z = 0.56$], showing an overall decrease in accuracy for language switching. This effect was moderated by the direction of the language switch. Fig. 3 plots the time course of looking to the target picture during different trial types according to block type. Infants who were tested in a dominant language block (L1–L2 switch) showed a more pronounced switch cost [$\text{mean}_{\text{same}} = 0.62$ (0.16), $\text{mean}_{\text{switched}} = 0.48$ (0.09), $t(11) = 3.61$, $P = 0.004$, $d_z = 1.04$] than infants tested in a nondominant language block (L2–L1 switch) [$\text{mean}_{\text{same}} = 0.58$ (0.097), $\text{mean}_{\text{switched}} = 0.54$ (0.14), $t(11) = 0.85$, $P = 0.42$, $d_z = 0.24$]. Note that whereas studies of language production often find a larger switch cost from L2 to L1 (17), our finding of a larger switch cost from L1 to L2 is consistent with both experimental and computational work in the auditory domain (28, 29, 37). This switch asymmetry is not reducible to infants simply showing better understanding of L1 target words relative to L2 target words. Although this explanation would correctly predict an L1–L2 switch cost, it would also predict something we did not observe: higher accuracy when listening to L2–L1 switches relative to sentences fully in L2. Thus, bilingual infants' performance was a function of both the carrier phrase and target word language, reflecting a switch cost.

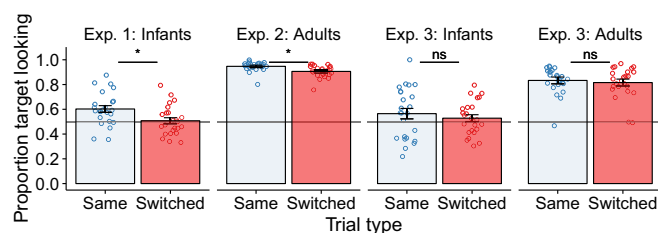


Fig. 2. Accuracy in looking to the target object from 360 to 2,000 ms after the target noun onset in Exps. 1 and 2 (intrasentential language switch; e.g., "Look! Find the *chien*!") and Exp. 3 (intersentential language switch; e.g., "That one looks fun! *Le chien*!"). Chance (0.5) is displayed by horizontal lines. Bars display means averaged over participants by trial type and age group. Error bars represent ± 1 SEM. Circles plot values for individual participants ($n = 24$ infants, 24 adults per study). In Exps. 1 and 2, both infants and adults looked to the target object significantly more during same-language than switched-language trials. However, in Exp. 3, neither infants nor adults showed significantly different looking to the same-language vs. switched-language trials. * $P < 0.05$, two-tailed; ns denotes a difference that was not statistically significant.

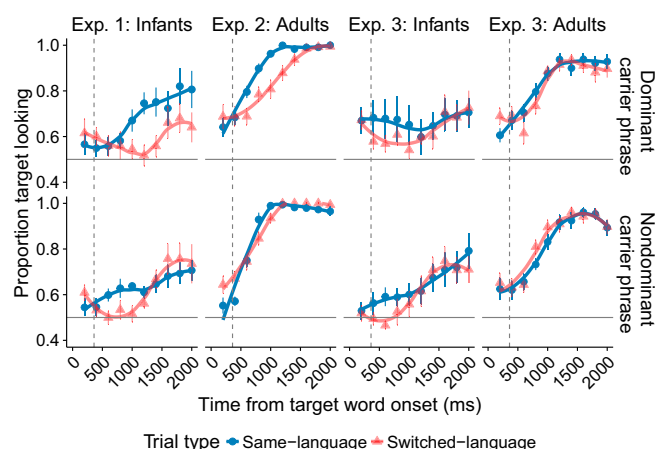


Fig. 3. Time course of participants' looking to the target picture after the target noun onset in Exp. 1 (intrasentential language switch; e.g., "Look! Find the *chien*!") and Exp. 2 (intersentential switch; e.g., "That one looks fun! *Le chien*!"). Results are displayed by experiment, trial type, age group, and block type. The dashed line indicates the beginning of the analysis window at 360 ms. Points display means averaged over participants, vertical lines represent ± 1 SEM, and red and blue lines show lowess-smoothed averages for switched-language and same-language trials. Chance (0.5) is displayed by the solid horizontal lines. In Exps. 1 and 2, when carrier phrases were in the dominant language (L1; $n = 12$ infants, 24 adults per study), participants were faster and more accurate to look to the target on the same-language than on the switched-language trials (L1–L2 switch). This switch cost was not observed when carrier phrases were in the nondominant language (L2–L1 switch), or for infants and adults in Exp. 3.

Next, we examined participants' task-evoked changes in pupil size over time, because pupil diameter can index cognitive load (33, 34). Infants' baseline-corrected pupil size was calculated over the course of the trial, as a function of block type and age group (displayed in Fig. 4). Sequential t tests were performed for each 200-ms time slice to compare pupil size during the same-language and switched-language trials. In the dominant language block (L1–L2 switch), pupil size was significantly larger ($P < 0.05$) during switched-language trials than during same-language trials from 1,000 to 2,000 ms after noun onset. Infants did not show significant pupil dilation in the nondominant language block. These pupillometry data provide convergent evidence that infants were under increased cognitive load when switching from the dominant to the nondominant language. Both accuracy and pupillometry data indicate a processing cost for language switches, which we interpret as evidence that bilingual infants control their languages as they listen to everyday sentences.

Exp. 2: Adults

Exp. 2 examined the continuity of language-control mechanisms across the lifespan by testing bilingual adults using the same stimuli and procedure as bilingual infants. This approach provided a highly conservative test for adults, as the words and sentences used in the experiment are highly familiar and learned early in life. Adults process high-frequency words rapidly (38), and thus participants might show a ceiling effect even when such words occur at a language switch. However, if bilingual adults do show a processing cost in this experiment, this would suggest that language control operates pervasively, even in very simple listening situations. Pupil dilation measures could be particularly revealing for adults, as pupillary responses are involuntary and thus would be unaffected by explicit response strategies that adults might deploy in this simple task (33).

We tested 24 highly proficient English–French bilingual adults, whose dominant (L1) and nondominant (L2) languages were

measured via self-report. Adults were told that they would see a video intended for infants. Unlike infants, who saw just one block of trials, adults saw both blocks in a counterbalanced order.

Adults showed high overall accuracy in looking to the target object during the 360- to 2,000-ms time window (Fig. 2). There was nonetheless evidence for a switch cost, as adults showed significantly greater looking to the target object during the same-language than the switched-language trials [$\text{mean}_{\text{same}} = 0.95$ (0.038), $\text{mean}_{\text{switched}} = 0.91$ (0.047), $t(23) = 4.81$, $P < 0.001$, $d_z = 0.98$]. Mirroring the asymmetry shown by infants, this was moderated by the direction of the language switch (Fig. 3). Adults' within-subject data confirmed a switch cost in the dominant language block (L1–L2 switch) [$\text{mean}_{\text{same}} = 0.95$ (0.033), $\text{mean}_{\text{switched}} = 0.88$ (0.086), $t(20) = 5.21$, $P < 0.001$, $d_z = 1.14$], but no switch cost in the nondominant language block (L2–L1 switch) [$\text{mean}_{\text{same}} = 0.94$ (0.058), $\text{mean}_{\text{switched}} = 0.94$ (0.038), $t(20) = 0.045$, $P = 0.96$, $d_z = 0.01$].

Next, we examined adults' pupil dilation in the same manner as Exp. 1 (Fig. 4). In the dominant language block (L1–L2 switch), pupil size was significantly larger during switched-language trials from 800 to 2,000 ms after target noun onset, and in the nondominant language block (L2–L1 switch) from 1,000 to 1,600 and 1,800 to 2,000 ms after target noun onset. Pupil sizes were not significantly different in other time slices ($P_s > 0.05$).

These results indicate that, like infants, bilingual adults control their languages during real-time sentence processing. For both groups, a language switch from L1 to L2 reduced the accuracy of looking to a labeled target, although accuracy was not affected for switches from L2 to L1. Moreover, processing language switches caused increased pupil dilation for both infants (L1–L2 switches) and adults (both L1–L2 and L2–L1 switches). Taken together, the consistency of data across measures shows that bilinguals, both at the beginning of development and in maturity, are affected by language switches when listening to the simplest of sentences.

Exp. 3: Cross-Sentence Switch

Exp. 3 was designed to more precisely investigate the locus of the effects observed in Exps. 1 and 2, and whether bilinguals

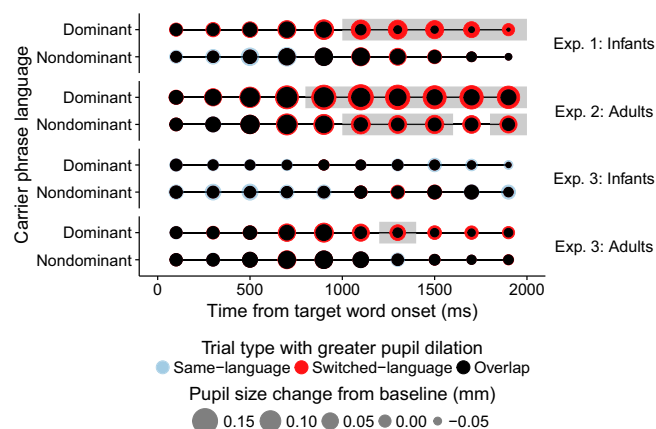


Fig. 4. Pupil size change (dilation) relative to baseline, from 0 to 2,000 ms after target noun onset in Exps. 1–3. Baseline was calculated by averaging pupil diameter on each trial in the time slice 200 ms before target noun onset. Results are displayed separately by age group, study, and block type. Red circles (switched-language trials) and blue circles (same-language trials) represent pupil diameter relative to baseline, and their overlap is black. Gray bars denote time slices where pupil size change was significantly larger during switched-language than same-language trials ($P < 0.05$, two-tailed). In Exps. 1 and 2, both infants and adults showed significantly more pupil dilation during switched-language trials. This effect was more apparent during dominant language blocks (L1–L2 switch) than nondominant language blocks (L2–L1 switch). In Exp. 3, adults showed pupil dilation only during the dominant block (L1–L2 switch), and infants did not show pupil dilation during either block.

encounter comprehension challenges for other types of language switches. In this experiment, participants heard language switches that occurred intersententially (“That one looks fun! *Le chien!*”), rather than intrasententially, as in Exps. 1 and 2. Both intra- and intersentential switches occur in bilingual speech (27, 31, 39). In this experiment, the switch occurred following a small, sentence-final silent pause and before the target word’s determiner. This slightly increased the temporal distance between the language switch and the target noun (500 ms on average). We expected that this manipulation would reduce processing effort associated with a language switch.

Participants were 24 English–French bilingual 20-mo-old infants, and 24 English–French bilingual adults. The stimuli and procedure were similar to Exps. 1 and 2, with the exception of the auditory stimuli. Here, auditory stimuli consisted of two utterances separated by a short natural pause: a carrier sentence that drew attention to the objects on the screen, followed by a noun–determiner pair, presented in either the same-language condition (“That one looks fun! The dog!”) or switched-language condition (“That one looks fun! *Le chien!*”). Infants completed one block and adults completed two blocks.

An examination of participants’ accuracy of looking to the target object did not reveal a significant switch cost for either group of participants (Figs. 2 and 3). Neither infants [$\text{mean}_{\text{same}} = 0.56$ (0.21), $\text{mean}_{\text{switched}} = 0.53$ (0.14), $t(23) = 0.71$, $P = 0.49$, $d_z = 0.14$] nor adults [$\text{mean}_{\text{same}} = 0.84$ (0.10), $\text{mean}_{\text{switched}} = 0.81$ (0.12), $t(23) = 1.13$, $P = 0.27$, $d_z = 0.23$] showed significantly more looking to the target object during same-language trials than during switched-language trials. Examining the data by block (L1 vs. L2) did not change this null effect. Infants did not show a significant switch cost in either the dominant language block (L1–L2 switch) [$\text{mean}_{\text{same}} = 0.56$ (0.20), $\text{mean}_{\text{switched}} = 0.53$ (0.15), $t(11) = 0.39$, $P = 0.70$, $d_z = 0.11$] or in the nondominant language block (L2–L1 switch) [$\text{mean}_{\text{same}} = 0.57$ (0.22), $\text{mean}_{\text{switched}} = 0.53$ (0.13), $t(11) = 0.59$, $P = 0.57$, $d_z = 0.17$]. Similarly, adults did not show a significant switch cost in either the dominant language block (L1–L2 switch) [$\text{mean}_{\text{same}} = 0.84$ (0.15), $\text{mean}_{\text{switched}} = 0.81$ (0.14), $t(23) = 0.96$, $P = 0.35$, $d_z = 0.20$] or in the nondominant language block (L2–L1 switch) [$\text{mean}_{\text{same}} = 0.83$ (0.12), $\text{mean}_{\text{switched}} = 0.82$ (0.13), $t(23) = 0.16$, $P = 0.87$, $d_z = 0.03$].

Pupillometry data were examined as in Exps. 1 and 2 from the onset of the target noun (Fig. 4). Infants did not show any significant difference in pupil size between same-language and switched-language trials for either block type (P s > 0.05). In the dominant-language block (L1–L2 switch), adults showed significantly larger pupil sizes ($P < 0.05$) during switched-language than single-language trials during a single 200-ms time slice from 1,200 to 1,400 ms. Adults did not show differences in pupil size in the nondominant language block (L2–L1 switch).

In sum, the switch cost observed in Exps. 1 and 2 was not observed to the same degree in Exp. 3. There was no evidence for different performance on same- and switched-language trials using eye-tracking measures of infants’ or adults’ looking, or on measures of infants’ pupil size. Adults, however, did show weak evidence of pupil dilation when they heard a switch from their L1 to their L2, although this effect was considerably less robust than in Exp. 2. These results show that hearing a language switch across a sentence boundary may necessitate some additional effort, but does not affect comprehension at a behavioral level. One explanation is that sentences form natural, compartmentalized processing units for both infants (40) and adults (41), facilitating comprehension of intersentential switches because they occur at an existing boundary for information processing. Relatedly, language switches in Exp. 3 occurred after a brief pause, which may have reduced the processing cost relative to the pause-free stimuli in Exps. 1 and 2. Another explanation is that the switch occurred after the determiner in Exp. 3, whereas it occurred before the determiner in Exps. 1 and 2. Whereas bilingual French speakers do produce

switches at both locations, they are more common after the determiner than before the determiner (35, 36). Given that the switch in Exp. 3 occurred at the less-frequent location, this explanation would predict a larger switch cost in Exp. 3 than in Exp. 2, which is the opposite of what we observed. Future work will be needed to explore how the processing of language switches interacts with particular linguistic structures, such as determiners (42, 43).

General Discussion

These experiments confirmed the hypothesis that bilingual infants and adults monitor and control their languages while listening. Bilinguals at both ages incurred a processing cost when hearing language switches, indexed by less-accurate word recognition and increased pupil dilation. Rather than indicating language difficulties, we argue that this represents an efficient strategy for bilinguals. Sounds and words from a particular language tend to occur in sequence. By capitalizing on these regularities and preferentially activating the currently heard language, bilinguals can speed language processing overall. Thus, a cost for language switching can be seen as a side effect of efficient bilingual processing. Importantly, our results indicate that language switches do not always lead to processing difficulties. Switches that occurred at a natural processing breakpoint—a sentence boundary—did not impair comprehension.

This work provides insight into fundamental questions about the mind’s ability to cope with complex language environments, exemplified by bilingualism. First, these results address a longstanding question about bilingual language acquisition: whether or not bilingual infants’ early representations distinguish between their languages (4, 5, 12). We have found evidence that bilingual infants preferentially activate the currently heard language, yielding a processing cost for language switches. This result would not be possible unless infants had begun to represent words in separable language systems. Our work thus provides experimental evidence of language differentiation in bilingual infants’ word representations. Such an ability is likely an important contributor to bilingual infants’ remarkable ability to navigate bilingual environments, and to learn two languages simultaneously.

Second, whereas many theories of bilingualism have pointed to the important role of language monitoring and control during speech production (44, 45), our research demonstrates the operation of similar mechanisms in language comprehension across the lifespan. Even when listening to the simplest of sentences, bilingual infants and adults preferentially activate the expected language and/or inhibit the other language. Although our findings do not preclude some activation of both languages during speech comprehension (21, 32), they do demonstrate stronger activation of the expected language. We argue that this contributes to efficient and fluent speech comprehension. An important future direction will be to investigate whether bilinguals modulate their language control during listening as a function of situation; for example, bilinguals may keep their languages more equally active when functioning in a bilingual mode (21, 46).

Finally, our results provide an additional explanation of why bilinguals show cognitive advantages across the lifespan (47). Leading theories have attributed these benefits to bilinguals’ practice in engaging language control during language production (19). However, there is evidence for cognitive benefits even in bilingual infants who do not yet produce speech (48, 49), rendering this single explanation impossible. With convergent evidence across ages and methods, our results reveal that bilinguals adapt to their unique language environments by monitoring, controlling, and switching between their two languages during comprehension. Practice doing so, we propose, trains information processing abilities beyond the domain of language. The cognitive benefits enjoyed by bilinguals are likely to accrue over time from everyday listening experience.

Methods

This research was approved by the Human Research Ethics Committee at Concordia University and the Institutional Review Board at Princeton University. Participants (adults) or their parents (infants) provided informed consent before participation.

Participants.

Exp. 1: Infants. Infants (11 females, 13 males) ranged in age from 19 mo, 3 d to 21 mo, 16 d (mean = 20 mo, 15 d), were born full term (37+ wk gestation), and had no reported major health or developmental problems. Infants were growing up in Montreal, Canada, and were recruited from a database of families interested in research. A target sample size of 24 infants was chosen based on similar studies in the field. All infants met the following preestablished inclusion criteria for bilingualism: they were exposed to both English and French regularly from birth, heard each language 25–75% of the time, and had no systematic exposure to a third language. Fourteen infants were English-dominant and 10 were French-dominant, determined by the language they heard most often, or by maternal language dominance for one infant who had equal exposure to the two languages. Infants heard their dominant language an average of 61% of the time (SD = 7, range = 50–74) and their nondominant language an average of 39% of the time (SD = 7, range = 26–50). Data from an additional 13 bilingual infants were excluded from analyses because of fussiness/disinterest (7 infants), technical problems (2 infants), reported health issues (2 infants), and parental interference (2 infants).

Productive vocabulary size in each language was assessed using the Words and Sentences version of the MacArthur–Bates Communicative Development Inventory (CDI) (50) and its adaptation to Quebec French (51). One infant was missing both CDIs, and one infant was missing the French CDI. Descriptive measures are reported for all data that were available. Average dominant language vocabulary size was 97 (SD = 72, range = 2–282), and average nondominant language vocabulary size was 63 (SD = 82, range = 4–333). Infants produced an average of 36 (SD = 39, range = 2–145) translation equivalents (cross-language synonyms). Total vocabulary size was calculated by summing the total number of words infants produced across both of their languages, which averaged 164 (SD = 130, range = 6–462). Total conceptual vocabulary size was calculated by subtracting the number of translation equivalents infants knew from their total vocabulary size as an index of the number of concepts that had been lexicalized. Infants had an average conceptual vocabulary of 129 words (SD = 96, range = 4–348).

Exposure to language switching was measured using the Language Mixing Scale, a parental self-report measure of parents' intrasentential language mixing when interacting with their child (30). Scores averaged 12.5 of 30 (SD = 8.2, range = 0–24), where 0 is no mixing and 30 is frequent mixing. Scores were not available for three infants.

Exp. 2: Adults. Twenty-four bilingual adults (21 females, 3 males) ranged in age from 18 to 35 y old (mean = 22). All were attending an English-speaking university in Montreal, a city where both English and French are used in everyday life. Self-report data were gathered about their language background via the Language Experience and Proficiency Questionnaire (52). Predetermined inclusion criteria were that adults reported high proficiency for comprehension in both languages, with at least 7 of 10 in both English and French, and fewer than 3 of 10 in any additional spoken languages. In this sample, English proficiency in comprehension averaged 9.5 of 10 (range = 7–10) and production averaged 9.3 of 10 (range = 7–10). In French, proficiency in comprehension averaged 8.8 of 10 (range = 7–10) and production averaged 8.1 of 10 (range = 6–10). Seventeen adults were English-dominant, four were French-dominant, and three reported balanced dominance (they were excluded from analyses involving language dominance). For all but three adults, their dominant languages were also their first-learned languages. All participants had acquired their second language between birth and age 13 y. Adults' language switching practices were assessed using a modified version of the Language Mixing Scale (30), the measure we used with infants' parents. In this case, participants reported their language mixing when interacting with other bilingual adults, rather than with a child. Adults reported a mean score of 14.0 of 30 (SD = 6.9, range = 0–30; data were missing for one participant).

Exp. 3.

Infants. Infants (12 females, 12 males; 14 English-dominant, 10 French-dominant) ranged in age from 19 mo, 25 d to 21 mo, 6 d (mean = 20 mo, 15 d), and were from the same population as Exp. 1. Infants heard their dominant language an average of 62% of the time (SD = 7.0, range = 50–74) and their nondominant language an average of 38% of the time (SD = 7.5, range = 27–50). Data from an additional 15 bilingual infants were excluded from analyses because of fussiness/disinterest (9 infants), technical problems (1 infant), and reported health issues (5 infants). Average dominant language vocabulary size was 112 (SD = 108, range = 0–454), and average nondominant language vocabulary size was 56 (SD = 53, range = 0–236). Infants produced an average of 35 (SD = 46, range = 0–213) translation equivalents (cross-language synonyms).

Total vocabulary size averaged 169 (SD = 152, range = 26–690), and total conceptual vocabulary size averaged 134 words (SD = 109, range = 26–477). Infants' average Language Mixing Scale Score was 14.5 of 30 (SD = 9.4, range = 0–28). Scores were not available for four infants.

Adults. Twenty-four bilingual adults (21 females, 3 males; 19 English-dominant, 5 French-dominant) ranged in age from 19 to 28 y old (mean = 21), and were from the same population as Exp. 2. English proficiency in comprehension averaged 9.7 of 10 (range = 8–10) and production averaged 9.5 of 10 (range = 8–10). In French, proficiency in comprehension averaged 9 of 10 (range = 7–10) and production averaged 8.4 of 10 (range = 7–10). For all but four adults, their dominant languages were also their first-learned languages. All participants had acquired their second language between birth and age 11. Adults reported a mean score on the Language Mixing Scale (30) of 15.5 of 30 (SD = 7.2, range = 3–30).

Stimuli.

Visual stimuli. Visual stimuli consisted of high-resolution photographs of objects on a gray background, and were identical across Exps. 1–3. Two images were displayed side-by-side during each trial. The pairs of pictures shown on the test trials were dog/book, door/mouth, and cookie/foot. Side of presentation was counterbalanced within and across participants. For each stimulus pair, labels within and across languages were dissimilar-sounding (i.e., different onsets and rhymes, no cognates), and had the same French grammatical gender to prevent the possibility of using the gendered French articles *le* and *la* to predict the noun (43). Filler trial pairs were spoon/ear, hand/bird, and apple/toothbrush, and were included to reduce the proportion of switched-language trials.

Auditory stimuli.

Exps. 1 and 2. A female native English–French bilingual speaker recorded auditory stimuli using infant-directed speech. Carrier phrases and target words were recorded in English and French. The English carrier phrase was, "Look! Find the..." and the French carrier phrase was "Regarde! Trouve le/la..." Target words "dog," "book," "door," "mouth," "foot," "cookie," and their French translations were spliced into a language-matched carrier phrase (for same-language sentences) or a language-mismatched carrier phrase (for switched-language sentences). An identical token of each word was used in the two sentence types. Carrier phrases were recorded such that coarticulation cues would be consistent with the target word. For example, the target word "dog" was excised from a recording of "Find the dog!" and spliced to replace the word "doctor"/"docteur" from the sentences "Find the doctor!" and "Trouve le docteur!" Care was taken so that spliced versions sounded as natural as possible.

Exp. 3. A female native English–French bilingual speaker recorded auditory stimuli using infant-directed speech. On each trial, the stimulus consisted of a stand-alone carrier phrase that directed the participants' attention to the screen followed by a determiner–noun pair that labeled the target object either in the same language (e.g., "That one looks fun! The dog!") or in the switched language (e.g., "That one looks fun! Le chien!"). Carrier phrases varied across trials (Fig. S1). French carrier phrases were translations of English phrases. The same target words as used in Exps. 1 and 2 were used for Exp. 3, now paired with the determiner "the" (English) or "le/la" (French) to create a short stand-alone phrase. Unlike in Exps. 2 and 3, the determiner and target word were always produced in the same language. The carrier phrase and determiner were separated by a natural silent pause. The interval between the end of the final word in the carrier phrase and the onset of the target word (including the time it took to produce the determiner) was 500 ms on average (range: 329 ms–636 ms).

Procedure. Participants were seated in a quiet testing room ≈60 cm away from a Tobii T60-XL eye tracker, which gathered eye-gaze and pupil size data at a rate of 60 Hz. The experimenter controlled the experiment using Tobii Studio software from an adjacent room and was blind to the trial type presented. Infants sat on parents' laps, while parents listened to music on headphones and wore darkened sunglasses to avoid influencing the infant. Adult participants sat on a chair. The eye tracker was calibrated to the participants' eyes using a five-point infant calibration routine.

On each trial, an object pair appeared on the monitor in silence for ≈3 s. Next, the auditory stimuli were played, which for each experiment consisted of a carrier phrase followed by the target word. The pictures remained on screen after the target word was spoken. Each trial lasted 8 s (Exps. 1 and 2) or 9 s (Exp. 3). An attention-grabbing animation appeared at the center of the screen between trials.

Participants saw a total of 18 trials per block, such that the carrier phrase was in a consistent language (either English or French). Within each block, six trials were same-language trials in which the target word was in the same language as the carrier phrase. Six trials were switched-language trials, in which the target word was in a different language from the carrier phrase. There were also six same-language filler trials that were not included in

analyses. Trial orders were quasi-random, such that the same object pair never appeared on consecutive trials. Similarly, two switched-language trials never appeared consecutively. Infants were randomly assigned to either a dominant-language block or a nondominant language block, and adults completed both blocks (order counterbalanced).

Participants (adults) or parents (infants) completed questionnaires once the experiment was complete. Infants were given a certificate and a T-shirt, and adults were awarded course credit for their participation.

Analysis Overview. Data from same-language and switched-language trials were analyzed in a time window of 360–2,000 ms after the onset of the target word on each trial, using the R package *eyetrackingR* (53, 54). This window of analysis was chosen because ≈ 360 ms are necessary for infants to process a word and initiate an eye movement, and eye movements after 2,000 ms are less likely to reflect a response to the target word.

Proportion of looking-time data were averaged across trials then trial type for each participant. All *t* tests were performed with $\alpha = 0.05$, two-tailed. Effect sizes are reported as standardized difference scores, computed as $d_z = t/\sqrt{n}$.

Pupil-size analyses were performed by calculating a baseline pupil size per trial in the 200 ms before noun onset, and then subtracting this baseline from pupil size measurements on each trial. Trials excluded from the accuracy analysis and those

without baseline data were excluded (28% of trials for infants in Exp. 1; 18% of trials for adults in Exp. 2; 32% of trials for infants in Exp. 3; 30% of trials for adults in Exp. 3). Data were excluded from two adults in Exp. 2 and one adult in Exp. 3 who failed to contribute data from one or more trial types. Pupil size changes were averaged across the two eyes, and data were binned into 200-ms slices.

Additional Analyses. Correlations between processing of language switches, exposure to language switches, and degree of language dominance are detailed in *SI Additional Analyses*.

ACKNOWLEDGMENTS. We thank the members of our laboratories for help in creating stimuli and testing infants, particularly Liane Rebner, Alexandra Polonia, Chelsea da Estrela, and Melanie Brouillard; and the parents, infants, and students who participated. This work was supported by Natural Sciences and Engineering Council of Canada Grant 402470-2011 (to K.B.-H.); Fonds de Recherche du Québec-Société et Culture Grant 2012-NP-145009 (to K.B.-H.); National Institute of Child Health and Human Development Grant R03HD079779 (to C.L.-W. and K.B.-H.); a New Investigators Research Grant from the American Speech-Language-Hearing Foundation (to C.L.-W.); and a graduate fellowship from the Fonds de Recherche du Québec-Société et Culture (to E.M.-L.). K.B.-H. holds the Concordia University Research Chair in Bilingualism.

- Byers-Heinlein K, Fennell CT (2014) Perceptual narrowing in the context of increased variation: Insights from bilingual infants. *Dev Psychobiol* 56:274–291.
- De Houwer A, Bornstein MH, De Coster S (2006) Early understanding of two words for the same thing: A CDI study of lexical comprehension in infant bilinguals. *Int J Biling* 10:331–347.
- Werker JF, Byers-Heinlein K (2008) Bilingualism in infancy: First steps in perception and comprehension. *Trends Cogn Sci* 12:144–151.
- Curtin S, Byers-Heinlein K, Werker JF (2011) Bilingual beginnings as a lens for theory development: PRIMIR in focus. *J Phonetics* 39:492–504.
- Genesee F (1989) Early bilingual development: One language or two? *J Child Lang* 16:161–179.
- Byers-Heinlein K, Burns TC, Werker JF (2010) The roots of bilingualism in newborns. *Psychol Sci* 21:343–348.
- Molnar M, Gervain J, Carreiras M (2014) Within-rhythm class native language discrimination abilities of Basque-Spanish monolingual and bilingual infants at 3.5 months of age. *Infancy* 19:326–337.
- Bosch L, Sebastián-Gallés N (2001) Evidence of early language discrimination abilities in infants from bilingual environments. *Infancy* 2:29–49.
- Weikum WM, et al. (2007) Visual language discrimination in infancy. *Science* 316:1159.
- Kuipers JR, Thierry G (2012) Event-related potential correlates of language change detection in bilingual toddlers. *Dev Cogn Neurosci* 2:97–102.
- Nazzi T, Jusczyk PW, Johnson EK (2000) Language discrimination by English-learning 5-month-olds: Effects of rhythm and familiarity. *J Mem Lang* 43:1–19.
- Byers-Heinlein K (2014) Languages as categories: Reframing the “one language or two” question in early bilingual development. *Lang Learn* 64:184–201.
- Antovich DM, Graf Estes K (February 3, 2017) Learning across languages: Bilingual experience supports dual language statistical word segmentation. *Dev Sci*, 10.1111/desc.12548.
- Gervain J, Werker JF (2013) Prosody cues word order in 7-month-old bilingual infants. *Nat Commun* 4:1490–1496.
- Genesee F, Boivin I, Nicoladis E (1996) Talking with strangers: A study of bilingual children's communicative competence. *Appl Psycholinguist* 17:427–442.
- Petitto LA, et al. (2001) Bilingual signed and spoken language acquisition from birth: Implications for the mechanisms underlying early bilingual language acquisition. *J Child Lang* 28:453–496.
- Meuter RF, Allport A (1999) Bilingual language switching in naming: Asymmetrical costs of language selection. *J Mem Lang* 40:25–40.
- Costa A, Santesteban M (2004) Lexical access in bilingual speech production: Evidence from language switching in highly proficient bilinguals and L2 learners. *J Mem Lang* 50:491–511.
- Green DW (1998) Mental control of the bilingual lexico-semantic system. *Biling Lang Cogn* 1:67–81.
- Dijkstra T, Van Heuven WJ (2002) The architecture of the bilingual word recognition system: From identification to decision. *Biling Lang Cogn* 5:175–197.
- Grosjean F (2001) The bilingual's language modes. *One Mind, Two Languages: Bilingual Language Processing*, ed Nicol JL (Blackwell, Oxford), pp 1–22.
- Bergelson E, Swingle D (2012) At 6–9 months, human infants know the meanings of many common nouns. *Proc Natl Acad Sci USA* 109:3253–3258.
- Fernald A, Pinto JP, Swingle D, Weinberg A, McRoberts GW (1998) Rapid gains in speed of verbal processing by infants in the 2nd year. *Psychol Sci* 9:228–231.
- Marchman VA, Fernald A (2008) Speed of word recognition and vocabulary knowledge in infancy predict cognitive and language outcomes in later childhood. *Dev Sci* 11:F9–F16.
- Hurtado N, Grütter T, Marchman VA, Fernald A (2014) Relative language exposure, processing efficiency and vocabulary in Spanish-English bilingual toddlers. *Biling Lang Cogn* 17:189–202.
- Bail A, Morini G, Newman RS (2015) Look at the gato! Code-switching in speech to toddlers. *J Child Lang* 42:1073–1101.
- Poplack S, Sankoff D, Miller C (1988) The social correlates and linguistic processes of lexical borrowing and assimilation. *Linguistics* 26:47–104.
- Jackson GM, Swanson R, Mullin A, Cunningham R, Jackson SR (2004) ERP correlates of a receptive language-switching task. *Q J Exp Psychol A* 57:223–240.
- Alvarez RP, Holcomb PJ, Grainger J (2003) Accessing word meaning in two languages: An event-related brain potential study of beginning bilinguals. *Brain Lang* 87:290–304.
- Byers-Heinlein K (2013) Parental language mixing: Its measurement and the relation of mixed input to young bilingual children's vocabulary size. *Biling Lang Cogn* 16:32–48.
- Poplack S (1980) Sometimes I'll start a sentence in Spanish y termino en Español: Toward a typology of code-switching. *Linguistics* 18:581–618.
- Spivey MJ, Marian V (1999) Cross talk between native and second languages: Partial activation of an irrelevant lexicon. *Psychol Sci* 10:281–284.
- Beatty J (1982) Task-evoked pupillary responses, processing load, and the structure of processing resources. *Psychol Bull* 91:276–292.
- Hepach R, Westermann G (2016) Pupillometry in infancy research. *J Cogn Dev* 17:359–377.
- Poplack S (1987) Contrasting patterns of code-switching in two communities. *Aspects of Multilingualism: Proceedings from the Fourth Nordic Symposium on Bilingualism*, eds Wande E, Anward J, Nordberg B, Steensland L, Thelander M (Acta Universitatis Upsaliensis, Uppsala University, Uppsala, Sweden), pp 51–77.
- Redouane R (2005) Linguistic constraints on codeswitching and codemixing of bilingual Moroccan Arabic-French speakers in Canada. *ISB4: Proceedings of the 4th International Symposium on Bilingualism*, eds Cohen J, McAlister KT, Rolstad K, MacSwan J (Cascadia Press, Somerville, MA), pp 1921–1933.
- Shook A, Marian V (2013) The bilingual language interaction network for comprehension of speech. *Biling (Camb Engl)* 16:304–324.
- Scarborough DL, Cortese C, Scarborough HS (1977) Frequency and repetition effects in lexical memory. *J Exp Psychol Hum Percept Perform* 3:1–17.
- Myers-Scotton C (1992) Comparing codeswitching and borrowing. *J Multiling Multicult Dev* 13:19–39.
- Mandel DR, Jusczyk PW, Nelson DG (1994) Does sentential prosody help infants organize and remember speech information? *Cognition* 53:155–180.
- Marslen-Wilson W, Tyler LK, Seidenberg M (1978) Sentence processing and the clause boundary. *Studies in the Perception of Language*, eds Levelt WJM, Flores d'Arcais GB (J. Wiley & Sons, Chichester, UK), pp 219–246.
- Dussias PE, Valdés Kroff JF, Guzzardo Tamargo RE, Gerfen C (2013) When gender and looking go hand in hand: Grammatical gender processing in L2 Spanish. *Stud Second Lang Acquis* 35:353–387.
- Lev-Williams C, Fernald A (2007) Young children learning Spanish make rapid use of grammatical gender in spoken word recognition. *Psychol Sci* 18:193–198.
- Green DW, Abutalebi J (2013) Language control in bilinguals: The adaptive control hypothesis. *J Cogn Psychol (Hove)* 25:515–530.
- Abutalebi J, et al. (2007) The neural cost of the auditory perception of language switches: An event-related functional magnetic resonance imaging study in bilinguals. *J Neurosci* 27:13762–13769.
- Green DW (2011) Language control in different contexts: The behavioral ecology of bilingual speakers. *Front Psychol* 2:103.
- Bialystok E, Craik FIM, Luk G (2012) Bilingualism: Consequences for mind and brain. *Trends Cogn Sci* 16:240–250.
- Kovács ÁM, Mehler J (2009) Flexible learning of multiple speech structures in bilingual infants. *Science* 325:611–612.
- Kovács ÁM, Mehler J (2009) Cognitive gains in 7-month-old bilingual infants. *Proc Natl Acad Sci USA* 106:6556–6560.
- Fenson L, et al. (2007) *MacArthur-Bates Communicative Development Inventories: User's Guide and Technical Manual* (Brookes, Baltimore), 2nd Ed.
- Boudreault M-C, Cabirol É-A, Trudeau N, Poulin-Dubois D, Sutton A (2007) Les inventaires MacArthur du développement de la communication: Validité et données normatives préliminaires. *Revue canadienne d'orthophonie et d'audiologie* 31:27–37.
- Marian V, Blumenfeld HK, Kaushanskaya M (2007) The language experience and proficiency questionnaire (LEAP-Q): Assessing language profiles in bilinguals and multilinguals. *J Speech Lang Hear Res* 50:940–967.
- Dink JW, Ferguson B (2015) *eyetrackingR: An R library for eye-tracking data analysis*. Available at www.eyetracking-r.com. Accessed July 6, 2017.
- R Core Team (2017) R: A language and environment for statistical computing. Available at <https://www.R-project.org/>. Accessed July 6, 2017.