Abstract

A key question in studies of cognitive development is whether bilingual environments impact higher-cognitive functions. Inconclusive evidence in search of a “bilingual cognitive advantage” has sparked debates on the reliability of these findings. Few studies with infants have examined this question, but most of them include small samples. The current study presents evidence from a large sample of 6- and 10-month-old monolingual- and bilingual-exposed infants (N=152), which includes a longitudinal subset (n=31), who completed a cueing attentional orienting task. The results suggest bilingual infants showed significant developmental gains in latency performance during the condition that was most cognitively demanding (Incongruent). The results also revealed bilingual infants’ performance was associated with their parents’ dual-language switching behavior. Taken together, these results provide support that bilingual experiences (i.e., dual-language mixing) influence infants’ shifting and orienting of attention.

Keywords: bilingualism, attention, shifting, infancy, language mixing, longitudinal

1. Introduction

Being bilingual provides a range of social benefits for individuals, including the opportunity to connect and communicate with individuals who speak either of their languages and learn from either (or both) cultures. However, whether bilingualism affords any cognitive benefits is a topic of great scientific contention. Some suggest that a bilingual environment improves performance on the cognitive mechanisms that support the management of two languages, such as attention and inhibitory control (Bialystok, 2015, 2017). A few studies with infants provide support for a "bilingual advantage" (Brito & Barr, 2012, 2014; Kovacs & Mehler, 2009a, 2009b; Comishen, Bialystok, & Adler, 2019; Singh et al., 2015), but new evidence is questioning the replicability of these effects (D'Souza, Brady, Haensel, & D'Souza, 2020; Kalashnikova, Pejovic, & Carreiras, 2020). In the present study, we used a large sample, along with a longitudinal subset, of 6- and 10-month-old infants to investigate whether bilingual-raised infants show better performance than monolingual-raised infants in a visuo-spatial attentional orienting task. In addition, we investigate which kind of bilingual experiences (i.e., parents' reporting of dual-language mixing and proportion of exposure) are associated with improved cognitive performance.

1.1 The "Elusive" Bilingual Advantage

The ability to select and produce words in one language, and effortlessly switch to another language is unique to bilinguals and multilinguals. According to the Inhibitory Control model (Green, 1998), bilinguals employ executive function mechanisms (such as attentional and inhibitory control) during selection and production of words in the corresponding language and inhibition of words in the language that is not in-use. Some suggest that bilingual environments that require consistent switching between the languages are training and enhancing the development and performance of executive function mechanisms beyond the linguistic domain—a notion known as the Bilingual Adaptation hypothesis (Bialystok, 2015; Bialystok, Craik, & Luk, 2012; Green & Abutalebi, 2013). Costa et al. (2009) hypothesized that the "bilingual advantage" may be related to the degree to which the bilingual uses both languages in their everyday life. Bilinguals who consistently use both languages in their everyday discourse may receive greater practice in attentional processes than bilinguals who use their languages separately in different social contexts (see also Bialystok, 2015; Green & Abutalebi, 2013). While both attention and inhibitory mechanisms support language processes, they may differ in how they are employed by bilinguals during everyday language use (e.g., Blanco-Elorrieta & Pylkkänen, 2016). For instance, inhibitory mechanisms are often employed during bilinguals' language switching in production, such as when trying to remember the name of a concept in one language (Green, 1998), whereas attention is more often engaged in language switching during comprehension (Blanco-Elorrieta & Pylkkänen, 2016). Currently, theoretical frameworks are shifting their focus towards understanding the relation between bilingualism and attentional mechanisms (Bialystok, 2017), especially during a period of language acquisition when bilingual-learning infants manage their languages but are unable to produce them yet.

Attentional orienting (i.e., the ability to engage, disengage and shift focus to sensory events) is one attentional mechanism that is an integral part of infants' language acquisition (Molnar, Alemán Bañon, Mancini, & Caffarra, 2020; Tenenbaum, Amso, Abar, & Sheinkopf, 2014). For instance, 8-month-old bilingual infants are more likely than monolingual infants to orient their visual attention to a speaker's mouth to successfully distinguish language switches during a silent video of someone speaking (Sebastián-Gallés, Albareda-Castellot, Weikum, & Werker, 2012; Weikum et al., 2007). In comparison to monolingual-raised infants, bilingual infants tend to look longer at a speaker's mouth more than the eyes, earlier in development and for a longer developmental period (Pons, Bosch, & Lewkowicz, 2015; see also Ayneto & Sebastián-Gallés, 2017). Orienting attention to a speaker's mouth is associated with bilinguals' retention of new words (Weatherhead, Arredondo, Nácar-Garcia, & Werker, 2021), and infants' greater vocabulary knowledge (Tsang, Atagi, & Johnson, 2018). Various other reports of differences in how bilingual infants and toddlers allocate attentional resources for language, include: engaging the brain's theta waveband (associated with attention) during language perception and language processing (Nácar-Garcia et al., 2018), anticipating turn-taking between talkers who speak familiar over unfamiliar languages (Atagi & Johnson, 2020), and listening and attending longer to grammatically incorrect phrases (Molnar et al., 2020).

The studies reviewed above consider the impact of bilingual experiences on how infants exploit attentional resources during language acquisition, but less studied is the extent to which bilingual experiences may influence cognition beyond the language domain. The first reports that bilingual-raised infants, as young as 6-7 months of age, perform better than monolingual-raised infants on cognitive control tasks were published by Kovács and Mehler (2009a, 2009b; see also Brito & Barr, 2014; Comishen et al., 2019). In their work (Kovacs and Mehler, 2009a, 2009b; Comishen et al., 2019), infants were taught to associate an auditory or visual cue with a Target's location, and then tested on their ability to learn that the correct Target had switched to a different location (hence, akin to the attentional shifting Wisconsin card sorting task; Berg, 1948; Bialystok, 1999; Tran, Arredondo, & Yoshida, 2019). Both monolingual and bilingual infants anticipated the location of the Target during the learning phase (pre-switch), however, only bilingual infants were able to anticipate the new location of the Target (opposite side of the screen) during a post-switch phase. While several recent studies have not precisely replicated the infant bilingual advantage as initially reported, they have nonetheless revealed differences in how bilingual-learning infants allocated attentional resources (Arredondo, Aslin, & Werker, 2021; Kalashnikova et al., 2020; D'Souza et al., 2020; Tsui & Fennell, 2019). Kalashnikova et al. (2020; a registered report) found that bilinguals shifted their attention faster and fixated longer to a visual reward (similar results in D'Souza et al., 2020). Given these results, one possibility is that bilingual infants' abilities to disengage and shift their attention faster are associated with domain-general attentional orienting processes. That is, bilingual infants' increased reliance on attentional orienting during language acquisition (e.g., increased focus on the mouth) has impacts beyond the linguistic domain into the non-linguistic domain. In accordance with the Bilingual Adaptation hypothesis, bilingual-learning infants may show advanced performance in attentional orienting particularly of visual events.

Prior work on attentional orienting often focuses on how visuo-spatial events engage and shift the participant's attention across the visual field (Petersen & Posner, 2012). Developmentally, infants' eye movements begin as reflexive during the first months of life and become more goal-oriented around 4-months (Johnson, 1990, 1995). In the present study, we test the Bilingual Adaptation hypothesis by employing a simplified version of a spatial cueing task, in which infants were briefly presented with a cue either on the center-left or center-right side of a visual display and then a Target object in the same location (Congruent trials) or on the opposite side of the screen (Incongruent trials) where the cue originally appeared. This spatial cuing procedure is utilized as a measure of covert attention (Hood, 1993, 1995; Johnson, 1990; Posner, 1980; Posner & Cohen, 1984; Richards, 2000, 2001, 2005). Covert orienting of attention occurs when sensory information is processed in the visual field without the individual having moved their eyes (e.g., peripheral cue location; Hood, 1993; Richards, 2000, 2001, 2005).

Infants' ability (accuracy and latency performance) to shift their gaze to the side of the Target image, despite the brief cue, serves as a measure of orienting attention (Ross-Sheehy et al., 2015).

1.2 The Present Study

The debate about whether bilingualism advances cognitive control functions has intensified in the last decade (Duñabeitia & Carreiras, 2015; Hilchey et al., 2011; Paap, 2019; see review and meta-analysis by Gunnerud, Braak, Reikeras, Donolato, & Melby-Lervag, 2020). Replication efforts in psychology have encouraged scientists to take a hard look at the effects of sampling and publication bias (Adolph, Gilmore, Freeman, Sanderson, & Millman, 2012; Open Science Collaboration, 2015; de Bruin, Treccani, & Della Sala, 2015; Bialystok, Kroll, Green, MacWhinney, & Craik, 2015; Gunnerud et al., 2020). The challenges with attempts at replication include the presence of measurement variance across laboratories and strong theoretical preferences of the researchers (see Grundy & Bialystok, 2019 for an example). Caveats from previous studies include their small samples, lack of cross-sectional and longitudinal data, and failure to collect detailed information about the participants' bilingual environments. One way to address these limitations is for individual labs to recruit large samples or replicate effects with planned variations of their study design (as in D'Souza et al., 2020), and register their plans for data collection and analysis prior to publication (as in Kalashnikova et al., 2020), yet large sample studies with infants are still scarce.

Infancy provides a unique developmental period for examining the initial experiences that lead to changes in performance on cognitive control tasks. In the present study, we analyzed data from monolingual- and bilingual-exposed infants in two age groups (6- and 10-months; N=152) who were part of a larger research project, and who completed a non-linguistic visuo-spatial attentional orienting task (Posner, 1980). Using a large sample will help increase the statistical power to detect the true language group effects on infants' task performance. The study also included longitudinal data from a small subset (n=31) who completed tasks at both ages. Longitudinal samples provide a better estimate of age effects (since each participant is their own control) and reduce between-subject variance as compared to cross-sectional samples. In accordance with the Bilingual Adaptation perspective, we hypothesized that bilingual-raised infants may show more accurate and/or faster performance than monolinguals, when orienting/shifting attention to a Target stimulus following a congruent or incongruent cue. The study also investigated developmental differences at 6- and 10-months. One possibility is that improved performance by bilinguals will emerge at both ages. Another possibility is that like prior work (Comishen et al., 2019), a bilingual advantage will emerge at 6-months but may not be present at 10-months as seen in studies that include older infants (Tsui & Fennell, 2019). Lastly, and in accordance with the null hypothesis, both monolingual- and bilingual-raised infants may perform similarly.

The experience of growing up in a bilingual environment also ranges widely in childhood. The field is beginning to recognize bilingualism as a continuum of experiences, rather than categorically comparing bilingual and monolingual samples (Luk & Bialystok, 2013). During infancy, babies will range in the amount of dual-language exposure, who they hear their two languages from (e.g., primary caretaker), how often (e.g., daily), and/or whether babies hear dual-language mixing in their environments (Werker & Byers-Heinlein, 2008). The present study includes bilingual-learning infants who hear both languages daily from at least one of their parents for at least 20% of their daily life and lifetime. Parents completed a detailed questionnaire regarding their infant's dual-language exposure and dual-language mixing. Thus, we will also explore any associations between attentional orienting performance and variance in two key aspects of bilingual experiences (amount of exposure, language mixing). Importantly, this is the first study with infants to thoroughly examine whether quantitative aspects of bilingual experiences impact non-linguistic attentional abilities.

2. Materials and Method

2.1 Participants

Participating infants were part of a larger research project investigating the development of attentional orienting in the brain, and in which most infants (89 six-month-olds, 71 ten-month-olds) wore an fNIRS cap to measure brain activity (Arredondo, Aslin, & Werker, 2021). Participant criteria for the present study included: (a) meeting either the monolingual criteria (i.e., exposure to a primary language for at least 90% of their lifetime) or the bilingual criteria (i.e., exposure to a primary and secondary language for at least 20% in their daily life from birth) as recommended by prior infant research (Byers-Heinlein, 2015; Byers-Heinlein et al., 2019), (b) full-term birth (gestation ≥37 weeks) with no history of significant hearing, vision or health problems (including amblyopia, strabismus, and hearing loss), (c) completion of the first four blocks in the task (22 infants did not meet this criterion; 8 bilinguals and 3 monolinguals in each age group). From these criteria, a total of 183 infants' data were eligible. Families were recruited from advertisements on Facebook, and from the University of British Columbia Early Development Research Group database which recruits new parents at a maternity ward (in Vancouver, BC, Canada) at the time of the infant's birth. The study was approved by the University of British Columbia's ethical review boards and carried out in accordance with the Declaration of Helsinki and APA ethical standards; parents completed an informed consent form prior to taking part in the study.

The full set of data in the analyses includes infants who took part in cross-sectional sessions and in longitudinal sessions at both ages (6- and 10-months). Below we include descriptions of the entire data set included in the analyses and break them down by cross-sectional and longitudinal sessions as well. From the 183 eligible infants, data from 98 infants comprised the 6-month-old sample (M_{age} = 6.05 months, SD=.28; 42 females, 56 males), including 60 bilingual-learning and 38 monolingual-learning from birth. In addition, data from 85 infants comprised the 10-month-old sample (M_{age} = 10.58 months, SD=.32; 43 females, 42 males), including 37 bilingual-learning and 48 monolingual-learning from birth. From the 97 infants that met the bilingual criteria, the majority were exposed to two languages (86 infants, 88.66%). A small subset of infants was exposed to a third or fourth language for at least 10% in their daily life from birth: 10 infants (10.31%) were exposed to three languages, and one infant (0.01%) was exposed to four languages. See Appendix A for a complete list of the languages, in addition to English, that bilingual-learning infants in each age group were exposed to. Note that even if there was exposure to more than two languages, there was always at least 20% exposure to the second most common language.

Independent sample *t*-tests did not reveal differences in sex, age, or parents' education among bilingual and monolingual infants within each developmental group (6- and 10-month-olds). Within the bilingual group, independent sample *t*-tests did not reveal demographic differences between the 6- and 10-month-old infants, including sex, parents' education, parents' language proficiency in English and proficiency in the other language, parents' report on their dual-language mixing, and infants' dual-language exposure. See Table 1 for details.

2.1.1 Cross-Sectional Sample

From the subset of participants who took part in cross-sectional sessions: 67 infants comprised the 6-month-old sample (M_{age} = 6.04 months, SD=.25; 26 females, 41 males), including 45 bilingual-learning and 22 monolingual-learning from birth. In addition, 54 infants comprised the 10-month-old sample (M_{age} = 10.84 months, SD=.28; 27 females, 27 males), including 22 bilingual-learning and 32 monolingual-learning from birth.

2.1.2 Longitudinal Sample

A small subset of participants (n=31; 16 females, 15 males) took part in both sessions, at 6- and at 10-months of age. These included 15 bilingual-learning and 16 monolingual-learning infants. Importantly, the longitudinal sample was included in the group analysis with the larger cross-sectional sample, as well as a separate analysis of this sub-sample which provides an opportunity to assess the effect of reduced between-subject variance in the longitudinal subset.

2.2 Procedure

Infants were tested in a dimly lit, sound-attenuated room at an infant laboratory. Infants sat on their parent's lap and faced a computer monitor at an approximate distance of 65-cm. The parent wore opaque glasses to reduce bias. During testing, a baby lullaby song (with tones, no spoken language) played in the background at 50-db to soothe the infant. After the testing session, parents completed a questionnaire regarding the family's language and demographic backgrounds. At the end of the visit, infants received an honorary degree certificate, a lab newsletter, and a baby t-shirt as a thank you for their participation.

2.3 Measures: Parent Reports

2.3.1 Demographics Questionnaire

Parents reported on their child's health, birth weight, sex, and gestational age. Parents also reported their level of education, work status, and racial or ethnic background (see Appendix

B).

2.3.2 Language Background Questionnaire

Parents completed a one-on-one questionnaire with the experimenter (modified from Bosch & Sebastián-Gallés, 1997, 2001; see also Orena, Byers-Heinlein, & Polka, 2019), in which they reported on their infant's typical daily and weekly language exposure in the months following birth until the testing date; this included information about speakers who spent significant time with the child (e.g., at home, daycare, library, playgroups). This assessment allowed for a percentage calculation of how often each infant was exposed to English and other languages across their lifetime. From this assessment, we computed a proportion for the language that the infant was exposed to the most in comparison to (an)other language(s).

2.3.3 Language Mixing Scale (Byers-Heinlein, 2013)

Using a seven-point Likert scale (1=very true, 7=not at all true), parents reported how frequently they switched languages in the same sentence when speaking to their child. A total of four items were presented (Cronbach's alpha=.71), two of which assess inter-sentential language mixing ("I often start a sentence in English and then switch to speaking [other language]", "I often start a sentence in [other language] and then switch to speaking English") and two of which assess intra-sentential language mixing ("I often borrow an English word when speaking [other language]", "I often borrow a word from [other language] when speaking English"). We also asked parents to mark in which situations do they intra-sentential language mix when speaking English or the other language. Options included: "when I'm not sure of the word in English/other language", "no translation or only a poor translation exists for the word", "the word in English/other language is hard to pronounce", "when I'm teaching new words", "other times/not sure"). From this assessment, we computed an average score for intra-sentential language mixing and inter-sentential language mixing, as well as an average of both intra- and inter- language mixing.

2.4 Non-linguistic Infant Orienting with Attention task

Infants completed a visuo-spatial cueing attention task (Posner, 1980). For each trial, an attention getter (i.e., a yellow smiley face) was displayed (1000-ms) to focus the infant's gaze to the center of the screen. Then, a cueing asterisk appeared (150-ms), either on the center-left or center-right side of a visual display. A brief delay period followed (100-ms), in which a blank screen was presented (see also Ross-Sheehy, Schneegans, & Spencer, 2015). Finally, a Target image was displayed (1500-ms) either in the same location as where the cue originally appeared (Congruent condition) or on the opposite side of the screen (Incongruent condition); see Figure 1 and Appendix C for images of the stimuli.

Given the neuroimaging nature of the original research project, the following modifications were made to the task: First, the task only has two conditions (i.e., Congruent and Incongruent cues prior to Target object display), while prior work (e.g., Ross-Sheehy et al., 2015) uses additional conditions and cues (e.g., double cues, auditory cues). Second, the present study uses a consistent brief period of delay between the spatial cue and Target object across trials (i.e., 150ms), while prior work (e.g., Richards 2001, 2005) has varied the delay period (e.g., 450 ms, 875ms, 1300ms) to investigate inhibition of return and facilitation. Finally, the present study created blocks in which 5 trials of the same condition type were presented sequentially. Following each block, a resting period of 13-seconds was added prior to the next block. This last modification was done to accurately measure the increase and decrease of hemoglobin using fNIRS. Prior work instead has randomized the presentation of condition types across the task and do not include blocks of the same condition type. The task in the present study consisted of 12 experimental blocks, of which half were Congruent and the other half were Incongruent. Blocks were pseudo-randomized, such that the first four blocks always included two blocks of each condition. By this rule, infants were included in the analysis if they completed at least the first four blocks (as noted above). Each block consisted of five trials and was comprised of either only Congruent or Incongruent trials. The side of the cue and target image were pseudo-randomized, and no more than three trials per block appeared on the same side of the screen. Each trial lasted for 2,750-ms, and each block lasted approximately 14-seconds. A 13-seconds resting period, in which infants watched a spinning waterwheel, was included before and after each block. The total length of the task was approximately 5½-minutes.

2.4.1 Stimuli and Apparatus

The task was presented using SMI Experiment Suite 360 software on a Dell Precision laptop, which was connected to a 22" LCD color display monitor. A SONY AX33 4K Handycam camcorder was placed either on the top or bottom of the monitor screen to record the infants' eye movements and looking behavior in real time. All events were presented on a grey background (RGB:136,136,136). Targets consisted of six colorful objects: a yellow banana, a red shoe, a pink sippy cup, a yellow rubber ducky, a cookie, and a ball (see Appendix C). One object was presented in all five trials for a Congruent block and for an Incongruent block.

2.4.2 Gaze Coding

The coding guidelines were modeled after Richards (2001, 2005) and Ross-Sheehy et al. (2015) in which infants' ability to shift their gaze to the side of the Target image served as a measure of orienting attention (see also Posner, 1980). The videos were captured at a rate of 30 fps or 33-ms per frame. Each trial was coded for latency in directional response (center, left, right, away). First, each trial was coded for whether the infant was looking at the screen when the cue first appeared. During this portion of the coding (i.e., cue display), a trial was coded as “away” and therefore not considered in the performance analysis for the following reasons: if the infant’s eyes were closed, the infant looked away or their head was turned away from the screen, and/or the infant was crying with their eyes closed. Next, each trial in which the infant was looking at the screen (or had their eyes open towards the screen) was coded for a directional response of the first gaze shift following the cue. During this portion of the coding, trials were coded as “left”, “right”, “center”, or “away at Target onset”. In the case that the participant's first gaze shift was to a side of the screen, the trial was coded by the directional response (left, right). In the case that infants did not shift their gaze, the trial was coded as “center.” In the case that the infant watched the cue appear on the screen but looked away once the Target appeared or turned their head away from the screen, and/or the infant cried with their eyes closed during Target onset (following the cue), the trial was then coded as “away at Target onset”. Trials were then coded as “correct” if the participant’s first gaze shift following the cue was to the side of the Target (left, right). Trials were coded as “incorrect” if the participant did not shift their gaze (center), looked away at Target onset, or the first gaze shift was to the opposite side of the Target. Analyses on accuracy considered correct and incorrect trials (trials that were marked as “away” at cue onset were not included). Analyses on latency only considered correct trials, because latency during incorrect trials may be associated with inattention rather than actual orienting performance.

Four trained coders were randomly assigned videos for coding. Inter-coder reliability was established in the beginning by having each assistant code three training videos (from infants that were excluded in the present study due to not meeting participant criteria) and that ranged in difficulty: The first training video focused closely on the infant’s face, and the participating infant made clear directional responses; the next medium-difficulty video included an infant who often turned their head away from the screen and closed their eyes when the cue was displayed; and the last high-difficulty video included infants who often looked away from the screen, cried, and closed their eyes for long periods of time. Fleiss Kappa was computed to assess the agreement between the four coders. There was initial excellent agreement among the four coders, kappa=0.863, $p<.001$ (130 trials in total).

Given the length of the videos, coding is often a tedious task that may lead to minor errors. Therefore, each assistant re-coded a random set of 8-10 videos that were originally coded by another coder. In these instances, in which two coders coded a video, the coding by the second coder was retained. Discrepancies in the re-coding were few and reviewed by the first author, who met with the second coder to review agreements and discrepancies to ensure the second coder's responses were final; the coder was blind to which coding responses were agreements and discrepancies by the two coders. Cohen's Kappa was computed to assess the final agreement between the two coders in each video that was coded twice; all of which were above 0.88 and averaged 0.93 (kappa range=0.88-1, $p<.001$).

2.5 Analytical Strategy

To test the Bilingual Adaptation hypothesis, we examined monolingual and bilingual 6- and 10-month-olds' eye-gaze shifts in the Congruent versus Incongruent conditions of a visuospatial attentional orienting task. We used accuracy (correct and incorrect directional response to the Target side) and response latency (response time during correct directional shifts to the Target side) as the dependent variables. Specifically, logistic mixed-effects models for accuracy and linear mixed-effects models were fitted for the response latency. These analyses were conducted using R, version 4.0.4 (R Core Team, 2020), with the lmer and glmer functions in the lme4 packages (Bates, Mächler, Bolker, & Walker, 2015). The models were estimated with an unstructured covariance matrix. To test the hypothesis that bilinguals would outperform monolinguals and to investigate whether bilingual/monolingual performance varies by age, we fitted mixed-effects models that included the interaction among Congruence condition type (Congruent condition as the reference condition vs. Incongruent condition), infants' age in months (6- vs. 10-months), and language group (bilinguals as the reference group vs. monolinguals) as the fixed factors, a random intercept, and a random slope for the linear combination of age and congruence, varying over participants. We replicated this analysis with the longitudinal sample.

To examine whether bilingual experiences (amount of exposure, language mixing) impact attentional orienting performance, we also carried out similar but separate analyses with bilinguals, in which bilingualism variables were individually entered as moderators to test their effect on the random intercept, Congruence condition type (Congruent condition as the reference condition vs. Incongruent condition), performance across age (at 6- vs. at 10-months), and their interaction. Specifically, we used three scores from parents' dual-language mixing reports (i.e., intra-sentential language mixing, inter-sentential language mixing, and their average) and the infants' proportion of exposure to the primary language.

Simple effects from these models were obtained using the emmeans package (Lenth, Singmann, Love, Buerkner, & Herve, 2018) with *p*-values adjusted with Tukey's HSD corrections. Lastly, the following variables were considered as potential covariates: child's sex, and the average of parents' education. Each of these covariates was added individually to identify whether they predicted performance. The covariates did not alter the results presented below; see Appendix D for results that include covariates. The R code/syntax is available in Appendix G; the data can be accessed through OSF – https://osf.io/u28sg/

3. Results

On average, infants in the 6-month-old sample completed 50 trials (SD=11.82) and in the 10-month-old sample completed 44 trials (SD=12.61) out of the 60 trials in the task, before fussing out or task completion. There were no differences between the language groups on the number of trials that they completed at 6-months (bilinguals M=50.62, SD=12.58; monolinguals M=49.42, SD=12.58; $t(96)=-.49$, $p=.63$) or at 10-months (bilinguals M=47.65, SD=11.52; monolinguals M=42.33, SD=13.03; $t(83)=-1.96$, $p=.053$).

A total of 8,710 trials (6-month-olds= 4915 trials, 10-month-olds= 3795 trials) were completed by the participants. Of these trials, 994 trials (11.41%) were removed from the analyses due to infants having their eyes closed, looking away or turning their head away from the screen, or crying with eyes closed when the cue was displayed. That is, trials that were coded as “away” at cue onset were not included in the analyses. The accuracy model included all individual trials for each participant where a correct/incorrect directional response was recorded (see “Gaze Coding” section above) – a total of 7719 trials (88.62% of the completed trials). The latency model included all individual trials for each participant where a correct response was recorded – a total of 6055 trials (69.52% of the completed trials).

3.1 Between-Level (G)LMM: Age, Congruence Type, and Language Group Effects

First, we investigated whether bilingual-raised infants show more accurate and/or faster performance than monolinguals, when orienting/shifting attention to a Target stimulus following a congruent or incongruent cue. In the accuracy model for the full sample (Table 2, left panel) and for the longitudinal sample (Table 2, right panel), the analysis revealed a significant age effect signaling that 6-month-old infants showed better accuracy than 10-month-olds (see Table 1 for performance), however post-hoc analyses were not significant (full sample: log odds ratio= -0.11, SE = 0.10, $z = -1.09$, $p = 0.276$; longitudinal sample: log odds ratio= -0.001, SE = 0.16, $z = -0.003$, $p = 0.998$). Related to the age-effect, the accuracy model analysis also revealed a significant interaction between age and Congruence condition type (Table 2). Specifically, the 10-month-olds showed greater accuracy than the 6-month-olds at discriminating the difference between the Congruent and Incongruent conditions; difference estimates from the full sample (10-months – 6-months) = 1.13, SE = 0.20, $z = 5.55$, $p < .001$. Additional post-hoc analyses revealed that both 6- and 10-month-old infants performed better on the Congruent trials than the Incongruent trials (full sample 10-month-olds: log odds ratio = 2.16, SE = 0.17, $z = 12.67$, $p < .001$; longitudinal sample 10-month-olds: log odds ratio = 2.53, SE = .32, $z = 7.86$, $p < .001$; full sample 6-month-olds: log odds ratio = 1.03, SE = 0.11, $z = 9.08$, $p < .001$; longitudinal sample 6-month-olds: log odds ratio = 1.31, SE = .20, $z = 6.50$, $p < .001$). The 10-month-old infants showed significantly better accuracy during Congruent trials, as compared to 6-month-olds (full sample: log odds ratio= -0.67, SE = 0.14, $z = -4.78$, $p < .001$; longitudinal sample: log odds ratio = -0.61, SE = .23, $z = -2.69$, $p = .036$). However, the 10-month-old infants' performance suffered by the invalid cue during Incongruent trials, as compared to the 6-month-old infants (full sample: log odds ratio= 0.46, SE = 0.13, $z = 3.52$, $p = .002$; longitudinal sample: log odds ratio = 0.61, SE = .23, $z = 2.61$, $p = .045$).

In the latency model for the full sample (Table 3, left panel) and for the longitudinal sample (Table 3, right panel), the analysis revealed a significant Congruence condition type effect, in which infants responded faster during Congruent trials relative to Incongruent trials (full sample: beta = -64.20, SE = 4.47, t= -14.36, $p < .001$; longitudinal sample: beta = -79.70, SE = 8.95, t= -8.91, p < .001). There was also an effect of developmental age showing that infants were faster at 10-months than at 6-months (full sample: beta = -44.80, SE = 5.39, t= 8.32, p < .001; longitudinal sample: beta = 43.10, SE = 8.52, t= 5.06, p < .001).

The latency model analyses also revealed a significant three-way interaction between congruence condition, age, and language group. Post-hoc analyses revealed that both bilinguals and monolinguals showed faster responses during Congruent trials relative to Incongruent trials at 6- and at 10-months old (see Table 4 for post-hoc contrasts), and both 10-month-old bilinguals and monolinguals performed faster on the Congruent trials. However, the interaction stemmed from monolinguals showing no significant developmental differences for Incongruent performance at 6-months versus 10-months, while bilinguals were faster at 10-months relative to 6-months during Incongruent trials; see Table 4.

Finally, the full sample latency model analysis (but not the longitudinal results) revealed a condition type by language group interaction, which showed that bilingual infants were faster at discriminating the difference between the Congruent and Incongruent conditions than the monolingual infants; difference estimate (Bilingual – Monolingual) = -5.60, SE = 9.36, df = 188.96, t = -8.22, p < .001. Post-hoc results also revealed that both bilinguals and monolinguals responded faster during Congruent relative to Incongruent trials (bilinguals: beta = -66.40, SE = 6.18, t= 10.75, p < .001; monolinguals: beta = -60.80, SE = 7.03, t= -8.64, p < .001).

In addition, we carried out similar analyses in which we excluded data from participants whose parents reported multilingual exposure (11 participants). These analyses replicated the effects reported above, especially those of the full sample, and can be found in Appendix E.

3.3 Between-Level (G)LMM: Bilingual Effects

Next, we investigated whether bilingual-raised infants' performance was associated with specific bilingual experiences. Accuracy models did not reveal bilingual experience variables as significant moderators in bilingual infants' performance; these included infants' proportion of exposure to the primary language, parents' intra-sentential language mixing score (see Table 5), parents' inter-sentential language mixing score, and the average score (intra- and inter-) for language mixing.

Response latency models revealed that parents' intra-sentential language mixing score was a significant moderator in bilinguals' performance for Congruence condition type; see Table 5 and 6, Figure 2. Specifically, bilinguals were generally faster during Congruent trials than Incongruent trials, and the difference between these condition types was larger for infants whose parents reported more intra-sentential language mixing, when speaking to their child than those who reported less intra-sentential language mixing scores (see Table 6 and Figure 2). The rest of the models that incorporated bilingual infants' proportion of exposure to the primary language, parents' inter-sentential language mixing score, and the average score (intra and inter) for language mixing, were not significant moderators for response latency performance. We found similar results when excluding data from multilingual-exposed infants (11 participants), yet the significance degraded (see Appendix E, Table E.2) possibly due to a smaller sample.

Given these results, we explored parents' reporting on the situations in which they insert a word in the other language. All parents who completed the form marked at least one situation, except two parents in the 6-month-old sample and one parent in the 10-month-old sample. Parents were more likely to report situations in which an English word was inserted when speaking the other language (170 in total for both 6- and 10-month-old infants), than situations in which a word in the other language was inserted when speaking English (142 in total for both 6-

and 10-month-old infants). When speaking the other language, parents were more likely to report inserting a word in English during situations in which no translation or a poor translation existed for the word (31.21%) and when unsure of the word in the other language (30.64%). This was followed by options when teaching new words (17.34%), other situations or not sure (12.14%), and to a lesser extent when the word in the other language was hard to pronounce (6.94%). When speaking English, parents were more likely to report inserting a word in the other language during situations in which no translation or a poor translation existed for the word (27.97%) and when teaching new words (27.97%). This was followed by options when unsure of the English word (18.88%), other situations or not sure (16.78%), and to a lesser extent when the English word was hard to pronounce (7.69%).

4. Discussion

A fundamental question in studies investigating the development of cognitive control abilities is whether (and how) bilingual environments impact performance during infancy, even before language production. Using a large cross-sectional sample and a smaller longitudinal sample, the primary aim of the present study was to determine whether bilingual- and monolingual-raised infants show differences in performance for attentional orienting – a cognitive mechanism likely supporting cognitive control (i.e., attentional and inhibitory control) and especially relevant to bilingual language acquisition. In accordance with the Bilingual Adaptation hypothesis, we predicted bilingual-raised infants would show better performance than monolinguals. This hypothesis was supported by the response latency findings, in which bilingual infants showed better discrimination between the Congruent versus Incongruent conditions than the monolinguals. In addition, bilingual infants, but not monolinguals, showed significant developmental improvement in latency performance for the Incongruent trials.

Bilinguals' faster performance at 10-months during Incongruent trials – a more effortful condition of attentional orienting - may point to an advanced development of attentional orienting capabilities that likely emerges from dual-language experiences (discussed more below).

As noted earlier, prior studies have shown that bilingual infants disengage and shift attention faster to a visual target (Kalashnikova et al., 2020; D'Souza et al., 2020). Complementing and enriching previous findings, the present evidence suggests that latency for orienting and shifting attention improves with age for bilingual infants. Overall, both bilingual and monolingual infants revealed developmental differences in attentional orienting performance that were consistent with prior developmental evidence (Ross-Sheehy et al., 2015) showing superior spatial-attentional cueing with age: accurate gaze shifts to the Target during Congruent than Incongruent trials in which older infants showed better distinction between the conditions than younger infants, and faster latency performance for older than younger infants. Developmental differences in performance are likely due to a more mature system for visuo-motor control in the older infants (see Richards, 2000, 2001, 2005). There were no other differences between the monolingual- and bilingual-raised infants' performance in accuracy or reactive latency.

The final aim of the present study was to explore which factors from infants' bilingual environment, such as the infant's proportion of primary language exposure and the bilingual parent's dual-language switching behavior to their child, were associated with performance for attentional orienting. The proportion of time in which infants were exposed to the primary language was not associated with bilinguals' performance. However, we found that intra-sentential language mixing (i.e., word insertions in the other language during a sentence; *Look!*

It's a mariposa*! How cute!*) was a significant moderator of latency performance: infants who heard more intra-sentential language mixing from their caretaker showed faster performance during Congruent trials which led to a greater difference between Congruent and Incongruent latency performance. In contrast, infants who heard less intra-sentential language mixing showed longer response times during Congruent trials and a smaller difference between the two conditions. Taken together, these results provide support for the notion that the nature of bilingual differences in home language experience influence attention processes that underlie performance on attentional monitoring, as proposed by Costa et al. (2009). In sum, these results add support to prior work (D'Souza et al., 2020; Kalashnikova et al., 2020; Comishen et al., 2019) suggesting that bilingualism can impact infants' attentional mechanisms, especially when living in a linguistic environment in which intra-sentential language mixing is part of the infant's bilingual environment.

4.1 Attentional Orienting and Bilingual Code-Switching

Linguistic code-switching by children (Genesee et al., 1995) and their parents (Bail, Morini, & Newman, 2015; Byers-Heinlein, 2013; Goodz, 1989) is a common occurrence in bilingual home environments. Prior work suggests that proficient bilingual speakers are more likely to produce intra-sentential code-switches, while bilinguals who are less fluent are more likely to produce inter-sentential language mixing (Poplack, 1980). In the present study we also carried out exploratory correlations between dual-language mixing (inter-mixing, intra-mixing, and average mixing) and the infant's proportion of primary language exposure, parents' education, and parents' English/other language proficiency; these turned out non-significant (see Appendix G). The lack of a relation between dual-language mixing and proportion of primary language exposure could stem from measurement differences: the proportion of language exposure considered the child's overall environment since birth and with all speakers that they frequently encountered (e.g., other caretakers, siblings, grandparents, other family members, friends etc), while the dual-language mixing scale reported on the bilingual parent's rate of mixing behavior when speaking to their child.

Bilingual parents in the present study reported being equally proficient in both of their languages (see Table 1) but reported more instances in which English words were inserted when speaking the other language. Parents also reported that insertions occurred during linguistically appropriate situations, such as when no translation or a poor translation existed for the word, or when unsure of the word in the other language. Parents reported inserting words in the other language during similar situations when speaking English, but also for teaching new words in English. Indeed, insertions of other-language nouns are the most common utterances in bilingual parents' pattern of speech to their young children, even for parents who attempt the one-parent-one-language approach (Bail et al., 2015; Goodz, 1989). In the present study, insertions in English are likely typical and appropriate for this sample of families living in a city where English is the majority language. Nevertheless, research suggests that the amount of code-switching that parents engage in with their child varies widely from parent to parent (0-60% as reported by Bail et al., 2015).

Language switching requires the listener to retrieve a lexical item in the less active language, which is a more effortful type of cognitive processing (Abutalebi, Brambati, Annoni, Moro, Cappa, & Perani, 2007; Green, 1998; Thomas & Allport, 2000). Evidence from neuroimaging studies suggests that language switches engage cognitive control brain networks (Abutalebi et al., 2007; Blanco-Elorrieta & Pylkkänen, 2017). During production, bilingual adults tend to slow down prior to producing a switch from their non-dominant language to the dominant language (Costa & Santesteban, 2004; Guo, Liu, Misra, & Kroll, 2011; Misra, Guo, Bobb, & Kroll, 2012; Meuter & Allport, 1999). In language processing, young bilingual children and adults also recognize language switches within a sentence by showing a delay in word recognition, coupled with increased pupil dilation (associated with 'increased processing cost'), during intra-sentential language switches (Byers-Heinlein, Morin-Lessard, & Lew-Williams, 2017). While the dual-language processing work suggests that bilinguals are slower in word recognition, the present results suggest that with age bilingual infants perform faster in visual orienting attention. The two findings are not mutually exclusive. One possibility is that a bilingual environment is training attentional orienting mechanisms, and in this manner, attention may continue supporting efficient language selection for bilinguals. Theoretical perspectives on bilinguals' spoken word recognition (e.g., Bilingual Language Interaction Network for Comprehension of Speech; Shook & Marian, 2013) posit that a phono-lexical network emerges when lexical items co-occur or share a phonemic overlap across both languages. For instance, neuroimaging research shows that bilinguals engage brain regions in left frontal cortex and anterior cingulate (regions associated with language processing and attention) during word recognition tasks that present participants with single-language phono-lexical competitors (e.g., pear */pɛr/* vs. pan */pæn/*) and dual-language phono-lexical competitors (e.g., pear */pɛr/* vs. dog in Spanish *"perro"* [ˈpɛ.ro]). Bilinguals' brain activity in these studies was also associated with better cognitive control performance, but not for monolinguals (Marian et al., 2014; Marian, Bartolotti, Rochanavibhata, Bradley, & Hernandez, 2017; see also Arredondo, Hu, Satterfield, Tsutsumi, Gelman, & Kovelman, 2019; Arredondo, Hu, Satterfield, & Kovelman, 2017). In language processing, both languages are relatively co-active which slows down word selection, however, top-down mechanisms (such as attention) support the resolution of inter-language conflict (Blumenfeld & Marian, 2007, 2011, 2013; cf. Kroll, Dussias, Bice, & Perrotti, 2015). The present work is suggestive of the interactive relationship between bilingualism and altered top-down attentional mechanisms.

The present work is correlational in nature, nevertheless it suggests that bilingual and monolingual infants may rely on attentional orienting to track the unique features of each language (e.g., prosody, phonological and lexical cues) and when processing language switches. Our results suggest as well that this ability improves with age: at 6-months, infants' language processing systems are still sensitive to many properties of language, whereas by 9-months they are more specialized to the sound systems (Werker & Tees, 1984), the cues to word order (Gervain, Nespor et al., 2008) and to common words of their language(s) (Bergelson & Swingley, 2012; Tincoff & Jusczyk, 1999; Jusczyk et al., 1993a, b). By 7-months, bilingual infants can not only distinguish, but can also separately track the prosodic cues for each of their two languages (Gervain & Werker, 2013). Thus, it is possible that attentional orienting mechanisms are employed by pre-verbal bilingual infants to track their languages prior to their own language production and are enhanced by intra-sentential language switches. As attentional orienting improves with age and bilingual exposure, attentional mechanisms continue supporting language selection.

4.2 Limitations and Future Directions

The present study focused on attentional orienting, a mechanism that is one of the bases for cognitive control abilities. In this manner, the task employed in the present study does not employ flexible rule-learning as previous work on the bilingual cognitive advantage has done (Comishen et al., 2019; Kovács & Mehler, 2009a, 2009b). Switch tasks are more difficult for infants than the task used in the present study, which may also explain the lack of behavioral differences between the two groups. This is especially important since prior work suggests that tasks must be cognitively demanding to show differences in performance between bilinguals and monolinguals (Barac, Bialystok, Castro, & Sanchez, 2014).

Another limitation of the present work is its reliance on questionnaires, given that research suggests parents tend to under-report their language switching behaviors (Goodz, 1989; Genesee et al., 1995). Some suggest that parent self-reports of inter-sentential language switching are more accurate than intra-sentential switching. For instance, Bail et al. (2015) did not find significant correlations between parent ratings of intra-sentential switching and video-recorded parent-child behavior in the lab. Future research is needed to collect audio recordings of parent-child interactions along with detailed background information about their participants in order to better quantify aspects of bilinguals' environments. These variables can then be used in relation to task performance, to better understand the roots of any behavioral differences. As can be seen here, bilingualism is not merely a categorical variable, but rather a continuum of experiences (Luk & Bialystok, 2013; Reh, Arredondo, & Werker, 2018).

5. Conclusion

Using a large cross-sectional sample and a smaller longitudinal sample of infants, the present study found that bilingual-learning infants showed better performance on a visual attentional orienting task than monolinguals. Bilingual infants also showed significant improvement in latency performance from 6- to 10-months during Incongruent trials - a more effortful condition of attentional orienting. Critically, the present results linked dual-language intra-sentential mixing with bilingual infants' performance, suggesting that heterogeneity within a bilingual environment is one possible culprit limiting our understanding regarding the extent of any bilingual effects. These results suggest that adaptations in orienting and shifting attention in pre-verbal bilingual-learning infants likely result from experiencing an environment in which both languages are mixed within a sentence. Growing up in a bilingual environment in which speakers often mix both languages likely trains and possibly enhances the development and trajectory of attentional orienting mechanisms. Importantly, the present work provides the earliest developmental evidence for how dual-language switching by another speaker impacts attentional processes in the pre-verbal bilingual-learning infant.

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Table 1.
Average (standard deviation) for demographic information, task accuracy and latency performance for attentional orienting among 6- and 10-month-old bilingual and monolingual infants.

	Large Sample (N=183)			
	6-months old		10-months old	
	Monolinguals	**Bilinguals**	**Monolinguals**	**Bilinguals**
Demographics				
Female, Male	15, 23	27, 33	20, 28	23, 14
Age	6.04 (0.28)	6.05 (0.27)	10.58 (0.31)	10.57 (0.34)
Parents' education [a]	3.12 (0.91)	3.14 (0.88)	3.24 (0.87)	3.28 (0.93)
Primary language exposure (%)	97.80 (3.03)	66.90 (11.93)	98.61 (2.02)	64.89 (10.22)
Dual-language mixing score [b]	--	4.11 (1.43)	--	4.33 (1.34)
Intra-language mixing	--	3.82 (1.59)	--	3.93 (1.61)
Inter-language mixing	--	4.32 (1.63)	--	4.74 (1.46)
Parent English proficiency [c]	--	8.36 (1.45)	--	8.43 (1.73)
Parent other language proficiency [c]	--	8.57 (1.74)	--	8.38 (1.55)
Attention Orienting Task Performance				
Congruent accuracy (%)	85.46 (10.45)	88.04 (10.15)	91.74 (10.70)	93.42 (6.54)
Congruent latency (ms)	230.91 (43.07)	220.06 (52.42)	165.37 (40.26)	167.50 (46.44)
Incongruent accuracy (%)	71.19 (14.86)	71.79 (16.95)	58.02 (21.15)	60.97 (21.99)
Incongruent latency (ms)	271.82 (53.49)	289.83 (66.84)	243.46 (62.21)	232.33 (55.83)
	Longitudinal Sample (N=31)			
	6-months old		**10-months old**	
	Monolinguals	**Bilinguals**	**Monolinguals**	**Bilinguals**
Demographics				
Female, Male	6, 10	10,5	6, 10	10,5
Age	6.10 (0.30)	6.03 (0.36)	10.48 (0.36)	10.52 (0.40)
Parents' education [a]	3.16 (0.94)	3.29 (0.91)	3.19 (0.92)	3.29 (0.91)
Primary language exposure (%)	98.78 (1.90)	67.08 (12.08)	98.63 (2.25)	66.33 (10.53)
Dual-language mixing score [b]	--	4.21 (1.58)	--	4.14 (1.60)
Intra-language mixing	--	3.57 (2.02)	--	3.71 (2.00)
Inter-language mixing	--	4.86 (1.76)	--	4.57 (1.65)
Parent English proficiency [c]	--	8.02 (2.05)	--	8.00 (2.08)
Parent other language proficiency [c]	--	8.67 (1.58)	--	8.43 (1.79)
Attention Orienting Task Performance				
Congruent accuracy (%)	89.01 (8.62)	90.71 (6.56)	93.50 (5.80)	95.59 (4.65)
Congruent latency (ms)	224.27 (41.25)	221.59 (47.02)	165.06 (43.66)	160.80 (46.76)
Incongruent accuracy (%)	68.36 (14.34)	73.39 (15.48)	50.07 (20.69)	61.98 (25.22)
Incongruent latency (ms)	285.93 (58.23)	301.13 (76.69)	266.31 (57.84)	240.41 (64.41)

Notes.
[a] The parents' education score is an average from both parents. Options for responses on parents' education included: (1) primary school, some high school, high school, (2) some college/university, college certificate/diploma, trade school diploma, (3) Bachelor's degree, (4) Master's degree, (5) Doctoral degree, professional degree.

[b] The dual-language mixing score represents an average of four items using a Likert scale that ranged between 1 to 7, with 1= very true, 4=somewhat true, and 7= not at all true.
[c] The language proficiency scores represent an average of three items that asked parents about their abilities understanding, reading, and speaking English and their other language, using a Likert scale that ranged between 0 to 10, with 0 = none, 5= adequate, and 10 = perfect.

Table 2.

Results from the Logistic Mixed-Effects Models for accuracy performance in attentional orienting among 6- and 10-month-old bilingual and monolingual infants in the large cross-sectional sample (N=183) and longitudinal subset (n=31).

Outcome: Accuracy (%)	**Large sample (N=183)** Final Model (AIC = 7006.5)					**Longitudinal sample (n=31)** Final Model (AIC = 2406.6)				
	Logit	S.E.	*z*	*p*	*Odds Ratio*	Logit	S.E.	*z*	*p*	*Odds Ratio*
Intercept	1.20	0.37	3.24	0.001**	3.32	1.28	0.62	2.08	0.038*	3.60
Condition Type (Ref. Cong)	0.50	0.48	1.04	0.298	1.64	0.63	0.85	0.74	0.462	1.87
Age (unit: month)	0.16	0.05	3.22	0.001**	1.17	0.19	0.08	2.32	0.020*	1.20
Condition Type * Age	-0.27	0.07	-4.01	< .001***	0.77	-0.31	0.12	-2.59	0.010**	0.74
Group (Ref. Bilingual)	-0.37	0.52	-0.71	0.476	0.69	0.24	0.78	0.31	0.759	1.27
Condition Type * Group	0.35	0.66	0.53	0.596	1.42	-0.21	1.13	-0.18	0.854	0.81
Age * Group	0.02	0.07	0.25	0.801	1.02	-0.06	0.10	-0.66	0.512	0.94
Condition Type * Age * Group	-0.03	0.09	-0.36	0.722	0.97	0.00	0.16	0.02	0.984	1.00
pseudo R^2 for fixed effects only	10.56%					14.83%				
pseudo R^2 for fixed effects + random effects	18.54%					20.97%				

Note. ref. = reference group, cong. = congruent trials. Accuracy ~ Type + Month + Type * Month + Group + Group * Type + Group * Month + Group * Type * Month + (Type + Month + Type * Month | Subject)

* $p < .05$, ** $p < .01$, *** $p < .001$.

Table 3.

Results from the Linear Mixed-Effects Models for response latency performance in attentional orienting among 6- and 10-month-old bilingual and monolingual infants in the large cross-sectional sample (N=183) and longitudinal subset (n=31).

Outcome: Latency (unit: ms)	**Large sample (N=183)** Final Model (REML criterion at convergence: 75847.5)					**Longitudinal sample (n=31)** Final Model (REML criterion at convergence: 27468.3)				
	Estimate	S.E.	*df*	*p*	*t*	Estimate	S.E.	*df*	*p*	*t*
Intercept	297.19	15.15	107.42	.001***	19.62	307.17	25.69	29.17	.001***	11.96
Condition Type (Ref. Cong)	65.83	19.40	150.50	.001***	3.39	85.42	37.18	26.74	0.030*	2.30
Age (unit: month)	-12.45	1.81	101.59	.001***	-6.88	-13.76	2.88	30.07	.001***	-4.78
Condition Type * Age	0.02	2.48	202.71	0.995	0.01	-1.37	3.98	43.74	0.73	-0.34
Group (Ref. Bilingual)	8.40	23.45	104.88	0.721	0.36	-10.66	36.90	32.29	0.77	-0.29
Condition Type * Group	-63.30	29.53	138.10	0.034*	-2.14	-84.15	53.86	30.39	0.13	-1.56
Age * Group	-0.63	2.66	113.31	0.814	-0.24	1.49	4.15	34.01	0.72	0.36
Condition Type * Age * Group	7.43	3.60	218.92	0.040*	2.07	11.69	5.86	52.56	0.051^{+}	2.00
pseudo R^2 for fixed effects only	9.68%					11.42%				
pseudo R^2 for fixed effects + random effects	17.46%					20.02%				

Note. ref. = reference group, cong. = congruent trials. Latency ~ Type + Month + Type * Month + Group + Group * Type + Group * Month + Group * Type * Month + (Type + Month + Type * Month | Subject)

* $p < .05$, ** $p < .01$, *** $p < .001$.

Table 4.
Post-hoc results for the Linear Mixed-Effects Model 3-way interaction (Congruence condition type x Age x Language group) for latency performance among 6- and 10-month-old bilingual and monolingual infants in the large cross-sectional sample (N=183).

	Large sample (N=183)					Longitudinal sample (n=31)				
Contrast	Estimate	S.E.	df	t	*p*-value	Estimate	S.E.	df	t	*p*-value
Bilinguals										
Bi Congruent 6 - Bi Incongruent 6	-66.89	7.88	92.90	-8.48	.001***	-77.23	16.60	21.20	-4.66	0.003*
Bi Congruent 10 - Bi Incongruent 10	-65.89	8.00	69.50	-8.24	.001***	-71.77	13.10	26.90	-5.50	.001***
Bi Congruent 6 - Bi Congruent 10	50.10	7.73	89.30	6.48	.001***	55.04	11.50	30.10	4.78	.001***
Bi Incongruent 6 - Bi Incongruent 10	51.10	10.14	90.80	5.04	.001***	60.50	16.60	25.90	3.65	0.022*
Bi Congruent 6 - Bi Incongruent 10	-15.79	10.33	106.10	-1.53	0.790	-16.73	17.60	24.20	-0.95	0.977
Bi Incongruent 6 - Bi Congruent 10	116.99	9.07	114.90	12.90	.001***	132.27	17.00	22.30	7.77	.001***
Monolinguals										
Mono Congruent 6 - Mono Incongruent 6	-44.12	10.03	93.80	-4.40	.001***	-63.22	16.80	24.40	-3.77	0.018*
Mono Congruent 10 - Mono Incongruent 10	-76.87	7.64	93.20	-10.06	.001***	-104.51	14.00	40.00	-7.44	.001***
Mono Congruent 6 - Mono Congruent 10	55.43	8.30	104.40	6.68	.001***	49.07	12.00	38.40	4.10	0.005**
Mono Incongruent 6 - Mono Incongruent 10	22.69	10.49	116.40	2.16	0.382	7.77	17.40	34.20	0.45	1.000
Mono Congruent 6 - Mono Incongruent 10	-21.43	10.79	128.90	-1.99	0.495	-55.44	18.30	31.20	-3.03	0.081^{+}
Mono Incongruent 6 - Mono Congruent 10	99.55	10.14	114.80	9.82	.001***	112.28	17.20	25.90	6.54	.001***
Bilingual vs. Monolinguals (same age, same type)										
Bi Congruent 6 - Mono Congruent 6	-7.01	10.03	97.00	-0.70	0.997	1.70	16.60	29.80	0.10	1.000
Bi Incongruent 6 - Mono Incongruent 6	15.76	11.35	94.10	1.39	0.860	15.71	22.00	24.60	0.71	0.996
Bi Congruent 10 - Mono Congruent 10	-1.68	8.62	89.30	-0.20	1.000	-4.27	15.60	27.40	-0.28	1.000
Bi Incongruent 10 - Mono Incongruent 10	-12.66	11.61	82.30	-1.09	0.957	-37.02	21.30	28.70	-1.74	0.662

Note. Bi = Bilinguals. Mono = Monolinguals. 6 = 6-month-olds. 10 = 10-month-olds. * $p < .05$, ** $p < .01$, *** $p < .001$.

Table 5.

Attentional Orienting results from the Logistic Mixed-Effects Models for accuracy performance and Linear Mixed-Effects Model results for latency performance among 6- and 10-month-old bilingual infants, including the Intra-sentential mixing as a moderator effect.

	Outcome: Accuracy (%) AIC = 3646.7					Outcome: latency (unit: ms) REML criterion at convergence: 40329.3				
	Logit	S.E.	*z*	*p*	*Odds Ratio*	Est.	S.E.	df	*t*	*p*
Intercept	1.28	0.38	3.37	.001***	3.61	295.26	17.23	55.47	17.14	.001***
Condition Type (Ref. Cong)	0.43	0.51	0.83	0.41	1.53	72.31	22.58	63.51	3.20	0.002**
Age (unit: month)	0.14	0.05	2.84	0.004**	1.15	-12.23	1.96	53.32	-6.26	.001***
Condition Type * Age	-0.25	0.07	-3.57	.001***	0.78	-0.89	2.57	98.10	-0.35	0.73
Intra-Language Mixing Score (Intra)	-0.12	0.21	-0.57	0.57	0.89	3.59	10.66	44.09	0.34	0.74
Condition Type * Intra	0.12	0.30	0.40	0.69	1.13	-30.63	13.99	58.06	-2.19	0.033*
Age * Intra	-0.001	0.03	-0.04	0.97	1.00	0.71	1.21	41.85	0.59	0.56
Condition Type * Age * Intra	0.004	0.04	0.09	0.93	1.00	2.50	1.59	86.81	1.57	0.12
pseudo R^2 for fixed effects only	9.36%					11.20%				
pseudo R^2 for fixed effects + random effects	16.59%					20.87%				

Note for Accuracy model. ref. = reference group, cong. = congruent trials. Accuracy ~ Type + Month + Type * Month + Intra + Intra * Type + Intra * Month + Intra * Type * Month + (Type + Month + Type * Month | Subject)

Note for Latency model. ref. = reference group, cong. = congruent trials. Latency ~ Type + Month + Type * Month + Intra + Intra * Type + Intra * Month + Intra * Type * Month + (Type + Month + Type * Month | Subject)

* $p < .05$, ** $p < .01$, *** $p < .001$.

Table 6.

Post-hoc results for Condition type x Intra-Language mixing significant interaction in the Linear Mixed Model result for latency performance in the bilingual 6- and 10-month-old sample (N=92).

Intra-Mixing Average (Mean = 0, SD = 1.59)	Condition Type	Estimate	S.E.	df	lower.CL	upper.CL	*t*	*p*-value
+1 SD Intra-Language Mixing	Congruent Trials	214	7.41	74.3	199	229		
+1 SD Intra-Language Mixing	Incongruent Trials	262	9.11	68.0	244	280		
Mean Intra-Language Mixing	Congruent Trials	200	5.24	70.8	189	210		
Mean Intra-Language Mixing	Incongruent Trials	265	6.47	68.2	252	278		
-1 SD Intra-Language Mixing	Congruent Trials	185	7.49	69.2	170	200		
-1 SD Intra-Language Mixing	Incongruent Trials	268	9.23	63.4	250	287		
Contrasts								
+1 SD	Congruent - Incongruent	-47.69	9.24	65.3			-5.16	< .001***
Mean	Congruent - Incongruent	-65.34	6.55	66.6			-9.97	< .001***
-1 SD	Congruent - Incongruent	-83.00	9.26	61.5			-8.97	< .001***

Note. Lower.CL = lower confidence interval limit; upper.CL = upper confidence interval limit.

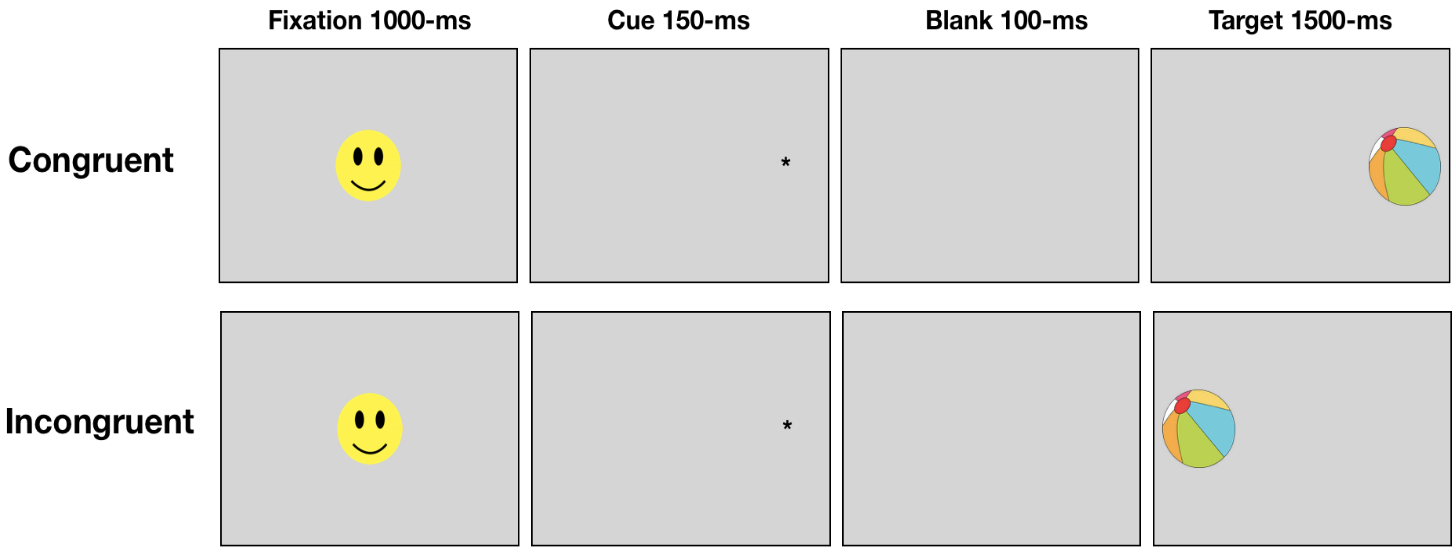

Figure 1. Example trials for the attentional orienting task: congruent trial on top row, incongruent trial on bottom row.

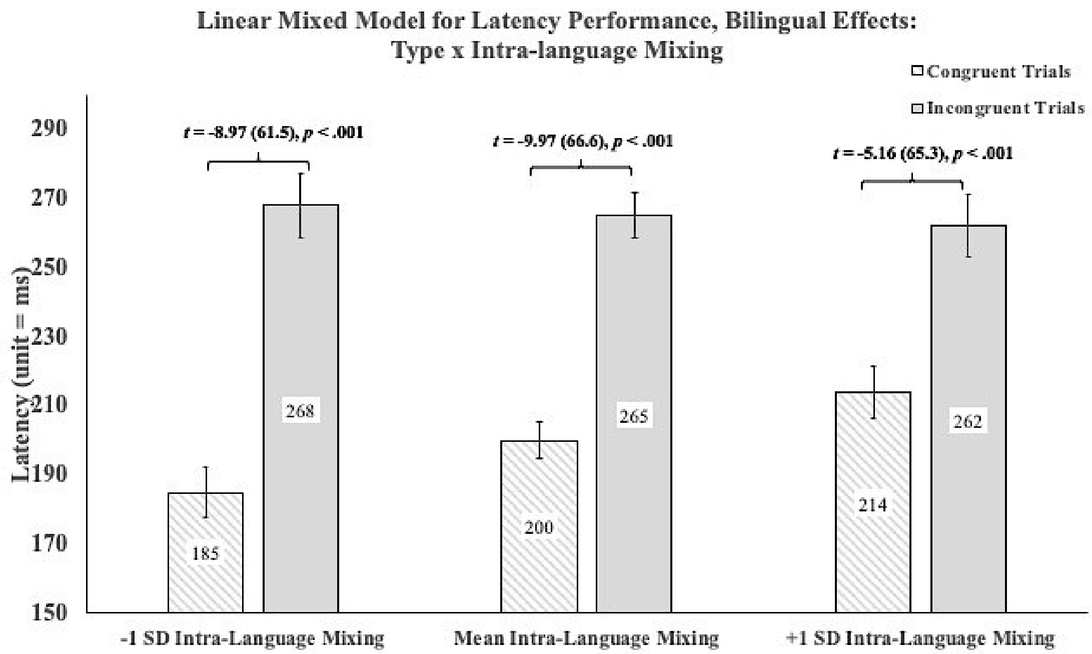

Figure 2. Bar graphs representing differences in latency performance for congruent and incongruent trials in the bilingual sample, by parents' report on dual-language intra-sentential mixing. The bars to the left (-1 SD) represent infants' performance from parents who report a high likelihood of mixing (e.g., 1=very true). The bars to the right (-1 SD) represent infants' performance from parents who report a low likelihood of mixing (e.g., 7=not at all true).

Appendix A

List of languages in addition to English being learned by bilingual participants. Numbers in columns correspond to the number of participants learning the language(s) in each age group. In all cases, at least two languages amounted to at least 20% or greater in daily and lifetime exposure. We also included infants who were exposed to a third language to at least 10% or greater in daily and lifetime exposure.

6-months old (n)	10-months old (n)	Language
12	10	Cantonese
7	5	Mandarin
2	3	Japanese
5	2	Spanish
2	0	German
2	1	Polish
4	2	French
2	1	Urdu
3	0	Tagalog
1	0	Russian
1	1	Arabic
1	0	Bengali
1	0	Kurdish
1	0	Bidayuh
1	0	Hindi
1	0	Portuguese
1	0	Aklanon
0	1	Vietnamese
0	1	Korean
0	1	Farsi
0	1	Bulgarian
3	0	Cantonese, Mandarin
1	0	Cantonese, Japanese
0	1	Cantonese, Korean

0	1	Cantonese, French
0	1	Mandarin, Turkish
0	1	Mandarin, French
1	0	Tagalog, Ilocano
0	1	Japanese, German
1	0	Urdu, German, Punjabi

Appendix B

Items included in the Demographics Questionnaire

Child Date of Birth: ______________________

MM / DD / YYYY

What was your child's birth weight? __ __ **lbs** __ __ **oz** OR __ __ __ __ **grams**

How many weeks gestation was your pregnancy? __ __ **weeks** __ __ **days**

Has your child ever been medically diagnosed with any of the following? Please check all that apply.

☐ Ankyloglossia (tongue-tie) ☐ Amblyopia (lazy eye) ☐ Strabismus (eye misalignment) ☐ ADD/ ADHD
☐ Other Visual Difficulties ☐ Hearing Difficulties ☐ Autism Spectrum Disorder
☐ Other, please specify:________________________ ☐ **Prefer not to disclose** ☐ **None of the above**

If there is a treatment plan for any of the above, please fill out the table below: ☐ **Prefer not to disclose**

Diagnosis	**Diagnosis Date**	**Treatment Plan** (Medication; Therapy)	**Start Date**	**End Date**

Has your child or anybody in your child's immediate family been diagnosed with colour blindness?
☐ **Yes** ☐ **No** ☐ **Prefer not to disclose**

If yes, who (child, parent, sibling)? _________________

Has your child or anybody in your child's immediate family been diagnosed with a language or communication disability? ☐ **Yes** ☐ **No** ☐ **Prefer not to disclose**

If yes, who (child, parent, sibling)? _________________

What was the diagnosis? __________________________

Does your child **currently** have an ear infection? ☐ **Yes** ☐ **No**

Has your child had any ear infections **in the past**? ☐ **Yes** ☐ **No**

If yes, at what age(s)? _____________________________

Does your child have a cold today? ☐ **Yes** ☐ **No**

If yes, does he/she have pressure/pain in ears (if known)? ☐ **Yes** ☐ **No**

Any other relevant information (related to health or language)? ______________________________________

Parent A's Highest Level of EDUCATION

☐ Primary School	☐ Some High School	☐ High School
☐ Some College/University	☐ College Certificate/Diploma	☐ Trade School Diploma
☐ Bachelor's Degree	☐ Master's Degree	☐ Doctoral Degree
☐ Professional Degree	☐ Not Applicable/Unknown	
☐ Other (please specify): ______________________________		

Parent B's Highest Level of EDUCATION

- ☐ Primary School
- ☐ Some High School
- ☐ High School
- ☐ Some College/University
- ☐ College Certificate/Diploma
- ☐ Trade School Diploma
- ☐ Bachelor's Degree
- ☐ Master's Degree
- ☐ Doctoral Degree
- ☐ Professional Degree
- ☐ Not Applicable/Unknown
- ☐ Other (please specify): ____

Parent A's OCCUPATIONAL Status (Check any/all that apply)

- ☐ Employed Full-Time
- ☐ Employed Part-Time
- ☐ Stay-at-home-Parent
- ☐ Student
- ☐ Unemployed
- ☐ Not Applicable/Unknown
- ☐ On Temporary Leave (e.g., maternity/paternity, sick, etc.; **please also check status when *not* on leave**)
- ☐ Other (please specify): ____

Parent B's OCCUPATIONAL Status (Check any/all that apply)

- ☐ Employed Full-Time
- ☐ Employed Part-Time
- ☐ Stay-at-home-Parent
- ☐ Student
- ☐ Unemployed
- ☐ Not Applicable/Unknown
- ☐ On Temporary Leave (e.g., maternity/paternity, sick, etc.; **please also check status when *not* on leave**)
- ☐ Other (please specify): ____

What are your child's ETHNIC ORIGINS? (Check any/all that apply)

- ☐ Aboriginal
- ☐ African
- ☐ Arab
- ☐ West Asian
- ☐ South Asian
- ☐ East and Southeast Asian
- ☐ Caribbean
- ☐ European
- ☐ Latin/Central/South American
- ☐ Pacific Islands
- ☐ Not Applicable/Unknown
- ☐ Other (please specify): ____

What CULTURE do you (and your partner) identify with? (Check any/all that apply)

- ☐ Aboriginal
- ☐ African
- ☐ Arab
- ☐ West Asian
- ☐ South Asian
- ☐ East and Southeast Asian
- ☐ Caribbean
- ☐ European
- ☐ Latin/Central/South American
- ☐ Pacific Islands
- ☐ Canadian/ USA
- ☐ Other (please specify): ____

Appendix C

Stimuli images for the ‘non-linguistic infant orienting with attention’ task.

Image of spinning waterwheel video. The video was played as a resting block (13-seconds) between blocks of Congruent and Incongruent condition

Image of Attention getter

Images of stimuli used as Target objects during Congruent and Incongruent trials

Appendix D

Table D1. Logistics mixed-effects models for accuracy performance with sex and parent education (average from both parents) as a covariate

Outcome: Accuracy	**Covariate: Sex**					**Covariate: Parent Education**				
	Final Model (Cov: **sex**, AIC = 7007.0)					Final Model (Cov: **p-educ**, AIC = 6877.6)				
	Logit	S.E.	*z*	*p*	*Odds Ratio*	Logit	S.E.	*z*	*p*	*Odds Ratio*
Intercept	0.94	0.44	2.16	0.03*	2.57	0.15	0.37	3.09	0.002**	1.16
Condition Type (Ref. Cong)	0.78	0.56	1.38	0.17	2.17	0.51	0.48	1.08	0.281	1.67
Age	0.19	0.06	3.30	.001***	1.21	0.16	0.05	3.24	0.001**	1.18
Condition Type * Age	-0.28	0.08	-3.68	.001***	0.76	-0.27	0.07	-3.97	.001***	0.77
Group (Ref. Bilingual)	-0.41	0.53	-0.79	0.43	0.66	-0.33	0.52	-0.65	0.517	0.72
Condition Type * Group	0.29	0.67	0.43	0.67	1.33	0.39	0.66	0.60	0.550	1.48
Age * Group	0.02	0.07	0.34	0.74	1.02	0.01	0.07	0.21	0.831	1.01
Condition Type * Age * Group	-0.02	0.09	-0.23	0.82	0.98	-0.04	0.09	-0.41	0.679	0.96
Cov.	0.54	0.52	1.05	0.30	1.72	-0.16	0.295	-0.54	0.591	0.85
Cov. * Condition Type	-0.38	0.66	-0.57	0.57	0.68	0.66	0.375	1.75	0.081+	1.93
Cov. * Age	-0.06	0.07	-0.91	0.36	0.94	0.02	0.038	0.47	0.637	1.02
Cov. * Condition Type * Age	0.00	0.09	0.03	0.98	1.00	-0.06	0.051	-1.23	0.218	0.94
pseudo R^2 for fixed effects only	10.78%					10.72%				
pseudo R^2 for fixed effects + random effects	18.58%					18.54%				

Note. P-educ = parent education, ref. = reference group, cong. = congruent trials, cov. = covariate. *Accuracy ~ Type + Month + Type * Month + Group + Group * Type + Group * Month + Group * Type * Month + Cov + Cov * Type + Cov * Month + Cov * Type * Month + (Type + Month + Type * Month | Subject)*
* $p < .05$, ** $p < .01$, *** $p < .001$.

Table D2. Linear mixed-effects models for latency performance with sex and parent education (average from both parents) as a covariate

Outcome: Latency	**Covariate: Sex**					**Covariate: Parent Education**				
	Final Model (Cov: **sex**, REML criterion at convergence: 75815.8)					Final Model (Cov: **p-educ**, REML criterion at convergence: 74109.2)				
	Est.	S.E.	df	*t*	*p*	Est.	S.E.	df	*t*	*p*
Intercept	294.71	19.461	98.56	15.14	< .001***	296.01	15.727	118.94	18.82	< .001***
Condition Type (Ref. Cong)	52.44	25.033	117.80	2.10	0.038*	67.22	20.762	145.67	3.24	0.001**
Age	-11.65	2.198	103.44	-5.30	< .001***	-12.39	1.904	114.55	-6.51	< .001***
Condition Type * Age	1.29	2.858	239.45	0.45	0.653	-0.05	2.462	261.24	-0.02	0.983
Group (Ref. Bilingual)	10.13	24.281	113.95	0.42	0.677	18.16	23.956	114.07	0.76	0.450
Condition Type * Group	-76.04	31.308	126.35	-2.43	0.017*	-74.56	31.890	125.31	-2.34	0.021*
Age * Group	-0.55	2.751	125.28	-0.20	0.842	-1.67	2.759	125.61	-0.61	0.546
Condition Type * Age * Group	8.69	3.575	252.06	2.43	0.016*	8.59	3.621	255.75	2.37	0.018*
Cov.	13.49	23.902	114.24	0.56	0.574	3.80	13.395	120.03	0.28	0.777
Cov. * Condition Type	31.34	30.852	127.89	1.02	0.312	20.45	18.427	147.78	1.11	0.269
Cov. * Age	-2.93	2.721	126.66	-1.08	0.284	0.33	1.547	130.29	0.21	0.832
Cov. * Condition Type * Age	-3.11	3.548	258.77	-0.88	0.382	-3.05	2.132	299.15	-1.43	0.154
pseudo R^2 for fixed effects only	10.30%					9.84%				
pseudo R^2 for fixed effects + random effects	18.08%					17.69%				

Note. P-educ = parent education, ref. = reference group, cong. = congruent trials, cov. = covariate. *Latency ~ Type + Month + Type * Month + Group + Group * Type + Group * Month + Group * Type * Month + Cov + Cov * Type + Cov * Month + Cov * Type * Month + (Type + Month + Type * Month | Subject)*

* $p < .05$, ** $p < .01$, *** $p < .001$.

Appendix E – Multilingual results

Table E.1. *Attentional Orienting results from the Logistics Mixed-Effects Models for accuracy performance and Linear Mixed-Effects Model results for latency performance among 6- and 10-month-old bilingual and monolingual infants in the large cross-sectional sample, that exclude multilinguals (N=172)*

	Outcome: Accuracy (%)					**Outcome: latency (unit: ms)**				
	Final Model (AIC = 6623.5)					Final Model (REML criterion at convergence: 71829.7)				
	Logit	S.E.	*z*	*p*	*Odds Ratio*	Est.	S.E.	df	*t*	*p*
Intercept	1.110	0.391	2.84	0.005**	3.033	299.82	16.78	115.85	17.87	.001***
Condition Type (Ref. Congruent)	0.662	0.506	1.31	0.19	1.939	60.19	21.34	130.52	2.82	0.006**
Age (in months)	0.175	0.053	3.28	0.001**	1.191	-12.70	2.00	113.97	-6.35	.001***
Condition Type * Month	-0.293	0.072	-4.09	.001***	0.746	0.60	2.56	230.80	0.24	0.813
Language Group (Ref. Bilingual)	-0.312	0.525	-0.59	0.553	0.732	13.38	25.22	111.98	0.53	0.597
Condition Type * Group	0.216	0.683	0.32	0.752	1.241	-64.37	32.19	112.90	-2.00	0.048*
Age * Group	0.005	0.068	0.08	0.940	1.005	-1.23	2.87	126.46	-0.43	0.670
Condition Type * Age * Group	-0.009	0.093	-0.10	0.923	0.991	7.53	3.69	220.24	2.04	0.042*
pseudo R^2 for fixed effects only	10.88%					9.51%				
pseudo R^2 for fixed effects + random effects	18.88%					17.76%				

Note. Accuracy ~ Type + Month + Type * Month + Group + Group * Type + Group * Month + Group * Type * Month + (Type + Month + Type * Month | Subject)

Note. RT ~ Type + Month + Type * Month + Group + Group * Type + Group * Month + Group * Type * Month + (Type + Month + Type * Month | Subject)

Table E.2.

Attentional Orienting results from the Logistics Mixed-Effects Models for accuracy performance and Linear Mixed-Effects Model results for latency performance among 6- and 10-month-old bilingual infants (excluding multilinguals), including the Intra-sentential mixing as a moderator effect.

	Outcome: Accuracy (%) AIC = 3646.7					**Outcome: latency (unit: ms)** REML criterion at convergence: 40329.3				
	Logit	S.E.	*z*	*p*	*Odds Ratio*	Est.	S.E.	df	*t*	*p*
Intercept	1.26	0.408	3.08	3.61	0.002**	296.68	18.593	49.58	.001***	15.96
Condition Type (Ref. Cong)	0.53	0.558	0.94	1.53	0.346	66.15	24.007	55.98	0.008**	2.76
Age (unit: month)	0.15	0.054	2.77	1.15	0.006**	-12.36	2.133	45.70	.001***	-5.79
Condition Type * Age	-0.27	0.077	-3.51	0.78	.001***	-0.17	2.747	80.96	0.950	-0.06
Intra-Language Mixing Score (Intra)	-0.12	0.228	-0.54	0.89	0.591	4.43	11.233	40.89	0.696	0.39
Condition Type * Intra	0.07	0.319	0.22	1.13	0.828	-29.31	14.650	51.99	0.051^{+}	-2.00
Age * Intra	0.00	0.030	0.00	1.00	0.999	0.66	1.287	38.68	0.612	0.51
Condition Type * Age * Intra	0.01	0.044	0.26	1.00	0.793	2.03	1.672	73.61	0.229	1.21
pseudo R^2 for fixed effects only	9.36%					11.20%				
pseudo R^2 for fixed effects + random effects	16.59%					20.87%				

Note for Accuracy model. ref. = reference group, cong. = congruent trials. Accuracy ~ Type + Month + Type * Month + Intra + Intra * Type + Intra * Month + Intra * Type * Month + (Type + Month + Type * Month | Subject)
Note for Latency model. ref. = reference group, cong. = congruent trials. Latency ~ Type + Month + Type * Month + Intra + Intra * Type + Intra * Month + Intra * Type * Month + (Type + Month + Type * Month | Subject)
* $p < .05$, ** $p < .01$, *** $p < .001$.

Appendix F

Table G. Correlations of variables among bilingual infants (Valid *N*s = 91~97).

	1	*2*	*3*	*4*	*5*	*6*	*7*
1. Inter Language Mixing Scores	-						
2. Intra Language Mixing Scores	.475***	-					
3. Language Mixing Average Score	.854***	.838***	-				
4. L1 exposure proportion	.005	-.069	-.022	-			
5. Parent education (average)	.126	.012	.080	.054	-		
6. Parent English language proficiency	.114	.052	.081	.057	.226*	-	
7. Parent other language proficiency	.037	.083	.058	.023	-.285^{+}	-.448***	-

Note. $^{+}$ $p < .06$, * $p < .05$, ** $p < .01$, *** $p < .001$.

Appendix G - R code

All original R codes were written and compiled using R-markdown and remain in the R-markdown format. Separate R code documents were created following the sequence of:

Larger sample models (including the complete sample)

```
---
title: "R & R (G)LMM whole sample - language group"
author: "MZhang"
date: "09/10/2021"
output:
  html_document: default
  pdf_document: default
---

```{r package, include=FALSE}
library(psych)
library(scales)
library(lme4)
library(lmerTest)
library(psych)
library(dplyr)
library(ggplot2)
library(emmeans)
library(stringr)
library(partR2)
```

1. loading the datafile
- The level-1 data
```{r load the level-1 data}
lvl.one <- read.csv("IBAD_LME_long.csv")
lvl.one <- within(lvl.one, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Trial <- factor(Trial)
  Type <- factor(Block)
  Group <- factor(Grp)
  AdjRT <- AdjRT*1000
  ACC <- factor(Accuracy)
  AdjRT[AdjRT=="NaN"] <- NA
  ACC[ACC=="NaN"] <- NA
})
describe(lvl.one,na.rm=TRUE)
```
- The level-2 data
```{r load the level-2 data}
lvl.two <- read.csv("IBAD_Cov_wide.csv")
lvl.two <- within(lvl.two, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Gender <- factor(Sex)
  MixAvg <- (IntraMixingAvg+InterMixingAvg)/2
```
```

````
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(lvl.two,na.rm=TRUE)
lvl.two.Bi <- lvl.two[which(lvl.two$MultiG==0),]
describe(lvl.two.Bi,na.rm=TRUE)
```
- Merge level-1&2 data
```{r merge level-1&2 data}
data.2lvl <- left_join(lvl.one, lvl.two,
              by = c("Mth"="Mth","Subj.ID"="Subj.ID"))
data.2lvl <- within(data.2lvl, {
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(data.2lvl,na.rm=TRUE)
```
# 2. build level 1 model
- 2.1 level 1 RT (within-exp level)
```{r model within-exp level RT, include=FALSE}
## null-model
RT.null <- lmer(AdjRT ~ 1 + (1 | Subj.ID), na.action=na.omit, data = data.2lvl, REML =
FALSE)
summary(RT.null)
## level-1 random intercept
RT.main <- lmer(AdjRT ~ Type + Mth_c + (Type + Mth_c | Subj.ID), na.action=na.omit, data =
data.2lvl, REML = FALSE)
summary(RT.main)
anova(RT.null,RT.main)
## random slope
RT.ranS <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.2lvl, REML = FALSE)
````

````
summary(RT.ranS)
anova(RT.main,RT.ranS)
```
- 2.2 final-level 1 RT model
```{r model within-exp level FINAL.RT}
RT.within <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.2lvl,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.within)
partR2(RT.within,R2_type="marginal")
partR2(RT.within,R2_type="conditional")
```
- 2.3 level 1 ACC (within-exp level)
```{r model within-exp level ACC, include=FALSE}
## null-model
ACC.null <- glmer(ACC ~ 1 + (1 | Subj.ID), na.action=na.omit, family = binomial, data =
data.2lvl)
summary(ACC.null)
## level-1 random intercept
ACC.main <- glmer(ACC ~ Type + Mth_c + (Type + Mth_c | Subj.ID), na.action=na.omit,
family = binomial, data = data.2lvl)
summary(ACC.main)
anova(ACC.null,ACC.main)
## random slope
ACC.ranS <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, family = binomial, data =
data.2lvl,control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=1e5)))
summary(ACC.ranS)
anova(ACC.main,ACC.ranS)
```
- 2.4 final-level 1 ACC model
```{r model within-exp level FINAL.ACC}
ACC.within <- ACC.ranS
summary(ACC.within)
partR2(ACC.within,R2_type="marginal")
partR2(ACC.within,R2_type="conditional")
```
# 3. build level 3 model (include langauge group as a moderator)
- 3.1 RT model
```{r model 3-level RT model}
RT.grp <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Group + Group*Type + Group*Mth_c
+ Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit, data =
data.2lvl, REML = TRUE, control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.grp)
partR2(RT.grp,R2_type="marginal")
partR2(RT.grp,R2_type="conditional")
````

````
```
- 3.2 ACC model
```{r model 3-level ACC model}
ACC.grp <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, family = binomial, data = data.2lvl,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.grp)
partR2(ACC.grp,R2_type="marginal")
partR2(ACC.grp,R2_type="conditional")
```
# 4. post-hoc analyses
- 4.1 RT model
```{r model post-hoc for RT model}
# main effect
emmeans(RT.grp, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(RT.grp, pairwise ~ Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
# interactions
emmeans(RT.grp, pairwise ~ Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit =
6077)
emmeans(RT.grp, pairwise ~ Group*Type,pbkrtest.limit = 6077)
emmeans(RT.grp, pairwise ~
Group*Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
```
_4.2 ACC model
```{r model post-hoc for ACC model}
# main effect
emmeans(ACC.grp, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(ACC.grp, pairwise ~ Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),lmerTest.limit =
6077)
# interactions
emmeans(ACC.grp, pairwise ~ Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit
= 6077)
```
````
````

Larger sample models (including only monolingual and bilingual infants, excluding multilingual infants)

```
---
title: "R & R (G)LMM only bilingual (exclude multilingual) - language group"
author: "MZhang"
date: "09/10/2021"
output:
  html_document: default
  pdf_document: default
---

```{r package, include=FALSE}
library(psych)
library(scales)
library(lme4)
library(lmerTest)
library(psych)
library(dplyr)
library(ggplot2)
library(emmeans)
library(stringr)
library(partR2)
```

1. loading the datafile
- The level-1 data
```{r load the level-1 data}
lvl.one <- read.csv("IBAD_LME_long.csv")
lvl.one <- within(lvl.one, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Trial <- factor(Trial)
  Type <- factor(Block)
  Group <- factor(Grp)
  AdjRT <- AdjRT*1000
  ACC <- factor(Accuracy)
  AdjRT[AdjRT=="NaN"] <- NA
  ACC[ACC=="NaN"] <- NA
})
describe(lvl.one,na.rm=TRUE)
```
- The level-2 data
```{r load the level-2 data}
lvl.two <- read.csv("IBAD_Cov_wide.csv")
lvl.two <- within(lvl.two, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
```
```

````
  Gender <- factor(Sex)
  MixAvg <- (IntraMixingAvg+InterMixingAvg)/2
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(lvl.two,na.rm=TRUE)
lvl.two.Bi <- lvl.two[which(lvl.two$MultiG==0),]
describe(lvl.two.Bi,na.rm=TRUE)
```
- Merge level-1&2 data
```{r merge level-1&2 data}
data.2lvl <- left_join(lvl.one, lvl.two,
            by = c("Mth"="Mth","Subj.ID"="Subj.ID"))
data.2lvl <- within(data.2lvl, {
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(data.2lvl,na.rm=TRUE)
data.2lvl.2 <- data.2lvl[which(data.2lvl$MultiG==0),]
describe(data.2lvl.2,na.rm=TRUE)
```
# 2. build level 1 model
- 2.1 level 1 RT (within-exp level)
```{r model within-exp level RT, include=FALSE}
## null-model
RT.null <- lmer(AdjRT ~ 1 + (1 | Subj.ID), na.action=na.omit, data = data.2lvl.2, REML =
FALSE)
summary(RT.null)
## level-1 random intercept
RT.main <- lmer(AdjRT ~ Type + Mth_c + (1 | Subj.ID), na.action=na.omit, data = data.2lvl.2,
REML = FALSE)
summary(RT.main)
````

````
anova(RT.null,RT.main)
## random slope
RT.ranS <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.2lvl.2, REML = FALSE)
summary(RT.ranS)
anova(RT.main,RT.ranS)
```
- 2.2 final-level 1 RT model
```{r model within-exp level FINAL.RT}
RT.within <- lmer(AdjRT ~ Type + Mth_c + (1 + Type + Mth_c | Subj.ID), na.action=na.omit,
data = data.2lvl.2, control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.within)
partR2(RT.within,R2_type="marginal")
partR2(RT.within,R2_type="conditional")
```
- 2.3 level 1 ACC (within-exp level)
```{r model within-exp level ACC, include=FALSE}
## null-model
ACC.null <- glmer(ACC ~ 1 + (1 | Subj.ID), na.action=na.omit, family = binomial, data =
data.2lvl.2)
summary(ACC.null)
## level-1 random intercept
ACC.main <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + (1 | Subj.ID), na.action=na.omit,
family = binomial, data = data.2lvl.2)
summary(ACC.main)
anova(ACC.null,ACC.main)
## random slope
ACC.ranS <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, family = binomial, data =
data.2lvl.2,control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=1e5)))
summary(ACC.ranS)
anova(ACC.main,ACC.ranS)
```
- 2.4 final-level 1 ACC model
```{r model within-exp level FINAL.ACC}
ACC.within <- ACC.ranS
summary(ACC.within)
partR2(ACC.within,R2_type="marginal")
partR2(ACC.within,R2_type="conditional")
```
# 3. build level 3 model (include langauge group as a moderator)
- 3.1 RT model
```{r model 3-level RT model}
RT.grp <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Group + Group*Type + Group*Mth_c
+ Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit, data =
````

````
data.2lvl.2, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.grp)
partR2(RT.grp,R2_type="marginal")
partR2(RT.grp,R2_type="conditional")
```
- 3.2 ACC model
```{r model 3-level ACC model}
ACC.grp <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, family = binomial, data = data.2lvl.2,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.grp)
partR2(ACC.grp,R2_type="marginal")
partR2(ACC.grp,R2_type="conditional")
```
# 4. post-hoc analyses
-4.1 RT model
```{r model post-hoc for RT model}
# main effect
emmeans(RT.grp, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(RT.grp, pairwise ~ Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
# interactions
emmeans(RT.grp, pairwise ~ Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit =
6077)
```
_4.2 ACC model
```{r model post-hoc for ACC model}
# main effect
emmeans(ACC.grp, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(ACC.grp, pairwise ~ Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),lmerTest.limit =
6077)
emmeans(ACC.grp, pairwise ~ Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),lmerTest.limit
= 6077)
    ```
````
````

Longitudinal infant only models (infants who participated in both time-point: 6-month and 10-month)

```
---
title: "R & R (G)LMM longitudinal - language group"
author: "MZhang"
date: "09/10/2021"
output:
  html_document: default
  pdf_document: default
---

```{r package, include=FALSE}
library(psych)
library(scales)
library(lme4)
library(lmerTest)
library(psych)
library(dplyr)
library(ggplot2)
library(emmeans)
library(stringr)
library(partR2)
#library(piecewiseSEM)
#library(r2glmm)
#library(sjmisc)
```

1. loading the datafile
- The level-1 data
```{r load the level-1 data}
lvl.one <- read.csv("IBAD_LME_long.csv")
lvl.one <- within(lvl.one, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Trial <- factor(Trial)
  Type <- factor(Block)
  Group <- factor(Grp)
  AdjRT <- AdjRT*1000
  ACC <- factor(Accuracy)
  AdjRT[AdjRT=="NaN"] <- NA
  ACC[ACC=="NaN"] <- NA
})
describe(lvl.one,na.rm=TRUE)
lvl.one.6 <- lvl.one[which(lvl.one$Mth==6),]
lvl.one.10 <- lvl.one[which(lvl.one$Mth==10),]
#create longitudinal dataset (N=31)
elmo6 <- subset(lvl.one.6,Trial==1,select=c(Subj.ID))
```
```

````
elmo10 <- subset(lvl.one.10,Trial==1,select=c(Subj.ID))
lvl.one.lgt.6 <- subset(lvl.one.6,Subj.ID==0)
for (i in 1:85) {
  dataset <- subset(lvl.one.6,Subj.ID==as.character(elmo10$Subj.ID[i]))
  lvl.one.lgt.6 <- rbind(lvl.one.lgt.6,dataset)
}
lvl.one.lgt.10 <- subset(lvl.one.10,Subj.ID==0)
for (i in 1:98) {
  dataset <- subset(lvl.one.10,Subj.ID==as.character(elmo6$Subj.ID[i]))
  lvl.one.lgt.10 <- rbind(lvl.one.lgt.10,dataset)
}
lvl.one.lgt<- rbind(lvl.one.lgt.6,lvl.one.lgt.10)
describe(lvl.one.lgt.6,na.rm=TRUE)
describe(lvl.one.lgt.10,na.rm=TRUE)
describe(lvl.one.lgt,na.rm=TRUE)
```
- The level-2 data
```{r load the level-2 data}
lvl.two <- read.csv("IBAD_Cov_wide.csv")
lvl.two <- within(lvl.two, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Gender <- factor(Sex)
  MixAvg <- (IntraMixingAvg+InterMixingAvg)/2
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(lvl.two,na.rm=TRUE)
```
- Merge level-1&2 data
```{r merge level-1&2 data}
data.2lvl <- left_join(lvl.one.lgt, lvl.two,
            by = c("Mth"="Mth","Subj.ID"="Subj.ID"))
data.2lvl <- within(data.2lvl, {
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
````

~~~
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(data.2lvl,na.rm=TRUE)
```
# 2. build level 1 model
- 2.1 level 1 RT (within-exp level)
```{r model within-exp level RT, include=FALSE}
## null-model
RT.null <- lmer(AdjRT ~ 1 + (1 | Subj.ID), na.action=na.omit, data = data.2lvl, REML =
FALSE)
summary(RT.null)
## level-1 random intercept
RT.main <- lmer(AdjRT ~ Type + Mth_c + (Type + Mth_c | Subj.ID), na.action=na.omit, data =
data.2lvl, REML = FALSE)
summary(RT.main)
anova(RT.null,RT.main)
## random slope
RT.ranS <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.2lvl, REML = FALSE)
summary(RT.ranS)
anova(RT.main,RT.ranS)
```
- 2.2 final-level 1 RT model
```{r model within-exp level FINAL.RT}
RT.within <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.2lvl,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.within)
partR2(RT.within,R2_type="marginal")
partR2(RT.within,R2_type="conditional")
```
- 2.3 level 1 ACC (within-exp level)
```{r model within-exp level ACC, include=FALSE}
## null-model
ACC.null <- glmer(ACC ~ 1 + (1 | Subj.ID), na.action=na.omit, family = binomial, data =
data.2lvl)
summary(ACC.null)
## level-1 random intercept
ACC.main <- glmer(ACC ~ Type + Mth_c + (Type + Mth_c | Subj.ID), na.action=na.omit,
family = binomial, data = data.2lvl)
summary(ACC.main)
anova(ACC.null,ACC.main)
## random slope
~~~

````
ACC.ranS <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, family = binomial, data =
data.2lvl,control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=1e5)))
summary(ACC.ranS)
anova(ACC.main,ACC.ranS)
```
- 2.4 final-level 1 ACC model
```{r model within-exp level FINAL.ACC}
ACC.within <- ACC.ranS
summary(ACC.within)
partR2(ACC.within,R2_type="marginal")
partR2(ACC.within,R2_type="conditional")
```
# 3. build level 3 model (include langauge group as a moderator)
- 3.1 RT model
```{r model 3-level RT model}
RT.grp <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Group + Group*Type + Group*Mth_c
+ Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit, data =
data.2lvl, REML = TRUE, control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.grp)
partR2(RT.grp,R2_type="marginal")
partR2(RT.grp,R2_type="conditional")
```
- 3.2 ACC model
```{r model 3-level ACC model}
ACC.grp <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, family = binomial, data = data.2lvl,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.grp)
partR2(ACC.grp,R2_type="marginal")
partR2(ACC.grp,R2_type="conditional")
```
# 4. post-hoc analyses
- 4.1 RT model
```{r model post-hoc for RT model}
# main effect
emmeans(RT.grp, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(RT.grp, pairwise ~ Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
# interactions
emmeans(RT.grp, pairwise ~ Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit =
6077)
emmeans(RT.grp, pairwise ~
Group*Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
```
_4.2 ACC model
````
````

```{r model post-hoc for ACC model}
# main effect
emmeans(ACC.grp, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(ACC.grp, pairwise ~ Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),lmerTest.limit =
6077)
# interactions
emmeans(ACC.grp, pairwise ~ Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit
= 6077)
```

Bilingual infant only models (including bilingual/multilingual infants, excluding monolingual infants)

```
---
title: "R & R (G)LMM bilingual only - language mixing"
author: "MZhang"
date: "09/10/2021"
output:
  html_document: default
  pdf_document: default
---

```{r package, include=FALSE}
library(psych)
library(scales)
library(lme4)
library(lmerTest)
library(psych)
library(dplyr)
library(ggplot2)
library(emmeans)
library(stringr)
library(partR2)
```

1. loading the datafile
- The level-1 data
```{r load the level-1 data}
lvl.one <- read.csv("IBAD_LME_long.csv")
lvl.one <- within(lvl.one, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Trial <- factor(Trial)
  Type <- factor(Block)
  Group <- factor(Grp)
  AdjRT <- AdjRT*1000
  ACC <- factor(Accuracy)
  AdjRT[AdjRT=="NaN"] <- NA
  ACC[ACC=="NaN"] <- NA
})
describe(lvl.one,na.rm=TRUE)
lvl.one.Bi <- lvl.one[which(lvl.one$Grp=="Bi"),]
describe(lvl.one.Bi,na.rm=TRUE)
```
- The level-2 data
```{r load the level-2 data}
lvl.two <- read.csv("IBAD_Cov_wide.csv")
lvl.two <- within(lvl.two, {
```
```

```
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Gender <- factor(Sex)
  MixAvg <- (IntraMixingAvg+InterMixingAvg)/2
  L1BL <- abs(Percent_L1-50) #sd 9.64
  Percent_L1[Percent_L1=="NaN"] <- NA
  Percent_otherL2exp[Percent_otherL2exp=="NaN"] <- NA
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
lvl.two.Bi <- lvl.two[which(lvl.two$LangG=="Bi"),]
describe(lvl.two,na.rm=TRUE)
describe(lvl.two.Bi,na.rm=TRUE)
data.cor <-
lvl.two.Bi[,c("L1BL","Percent_L1","Percent_otherL2exp","MixingAvg","IntraMixingAvg","Inte
rMixingAvg")]
cor.LM <- cor(data.cor,method="spearman",use="pairwise")
cor.LM
cor.test(data.cor$Percent_L1, data.cor$Percent_otherL2exp)
cor.test(data.cor$Percent_L1, data.cor$IntraMixingAvg)
cor.test(data.cor$Percent_L1, data.cor$InterMixingAvg)
cor.test(data.cor$Percent_otherL2exp, data.cor$IntraMixingAvg)
cor.test(data.cor$Percent_otherL2exp, data.cor$InterMixingAvg)
cor.test(data.cor$L1BL, data.cor$IntraMixingAvg)
cor.test(data.cor$L1BL, data.cor$InterMixingAvg)
cor.test(data.cor$IntraMixingAvg, data.cor$InterMixingAvg)
```

- Merge level-1&2 data

```{r merge level-1&2 data}
data.Bi <- left_join(lvl.one.Bi, lvl.two.Bi,
            by = c("Mth"="Mth","Subj.ID"="Subj.ID"))
data.Bi <- within(data.Bi, {
  MixingAvg <- MixingAvg-4.19 #sd 1.39
  IntraMixingAvg <- IntraMixingAvg-3.86 #sd 1.59
  InterMixingAvg <- InterMixingAvg-4.48 #sd 1.56
  LangP <- Percent_L1 + Percent_otherL2exp
  L1BL <- L1BL-15.18 #sd 9.64
  Percent_L1 <- Percent_L1-66.13 #sd 11.23
  Percent_otherL2exp <- Percent_otherL2exp-33.41 #sd 11.24
  P_L1 <- Percent_L1/100 #sd 0.1123
```

````
  P_L2 <- Percent_otherL2exp/100 #sd 0.1124
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(data.Bi,na.rm=TRUE)
Bi.6 <- data.Bi[which(data.Bi$Mth==6),]
describe(Bi.6,na.rm=TRUE)
Bi.10 <- data.Bi[which(data.Bi$Mth==10),]
describe(Bi.10,na.rm=TRUE)
describe(data.Bi$LangP,na.rm=TRUE)
hist(data.Bi$LangP)
```
# 2. build level 1 model
- 2.1 level 1 RT (within-exp level)
```{r model within-exp level RT, include=FALSE}
## null-model
RT.null <- lmer(AdjRT ~ 1 + (1 | Subj.ID), na.action=na.omit, data = data.Bi, REML = FALSE)
summary(RT.null)
## level-1 random intercept
RT.main <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type*Mth_c | Subj.ID),
na.action=na.omit, data = data.Bi, REML = FALSE)
summary(RT.main)
anova(RT.null,RT.main)
## random slope
RT.ranS <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.Bi, REML = FALSE)
summary(RT.ranS)
anova(RT.main,RT.ranS)
```
- 2.2 final-level 1 RT model
```{r model within-exp level FINAL.RT}
RT.within <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.Bi,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.within)
partR2(RT.within,R2_type="marginal")
partR2(RT.within,R2_type="conditional")
```
- 2.3 level 1 ACC (within-exp level)
````
````

````
```{r model within-exp level ACC, include=FALSE}
## null-model
ACC.null <- glmer(ACC ~ 1 + (1 | Subj.ID), na.action=na.omit, family = binomial, data =
data.Bi)
summary(ACC.null)
## level-1 random intercept
ACC.main <- glmer(ACC ~ Type + Mth_c + (1 | Subj.ID), na.action=na.omit, family = binomial,
data = data.Bi)
summary(ACC.main)
anova(ACC.null,ACC.main)
## random slope
ACC.ranS <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, family = binomial, data =
data.Bi,control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=1e5)))
summary(ACC.ranS)
anova(ACC.main,ACC.ranS)
```
- 2.4 final-level 1 ACC model
```{r model within-exp level FINAL.ACC}
ACC.within <- ACC.ranS
summary(ACC.within)
partR2(ACC.within,R2_type="marginal")
partR2(ACC.within,R2_type="conditional")
```
# 3. build level-2 model
## 3.1 Moderatoer: Mixing Average
- 3.1.1 RT model: MixAvg
```{r model 2-level RT MA model}
RT.MixAvg <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + MixingAvg + MixingAvg*Type
+ MixingAvg*Mth_c + MixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.MixAvg)
partR2(RT.MixAvg,R2_type="marginal")
partR2(RT.MixAvg,R2_type="conditional")
```
- 3.1.2 ACC model: MixAvg
```{r model 2-level ACC MA model}
ACC.MixAvg <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + MixingAvg + MixingAvg*Type
+ MixingAvg*Mth_c + MixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.MixAvg)
partR2(ACC.MixAvg,R2_type="marginal")
partR2(ACC.MixAvg,R2_type="conditional")
```
````

````
## 3.2 Moderatoer: Intra
- 3.2.1 RT model: Intra
```{r model 2-level RT Intra model}
RT.IntraMixAvg <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + IntraMixingAvg +
IntraMixingAvg*Type + IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type +
Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit, data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.IntraMixAvg)
partR2(RT.IntraMixAvg,R2_type="marginal")
partR2(RT.IntraMixAvg,R2_type="conditional")
```
- 3.2.2 ACC model: Intra
```{r model 2-level ACC Intra model}
ACC.IntraMixAvg <- glmer(ACC ~ Type + Mth_c + Mth_c*Type + IntraMixingAvg +
IntraMixingAvg*Type + IntraMixingAvg*Mth_c + IntraMixingAvg*Mth_c*Type + (1 + Type +
Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit, family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e6)))
summary(ACC.IntraMixAvg)
partR2(ACC.IntraMixAvg,R2_type="marginal")
partR2(ACC.IntraMixAvg,R2_type="conditional")
```
## 3.3 Moderatoer: Intra + Inter
- 3.3.1 RT model: Intra + Inter
```{r model 2-level RT Intra & Inter model}
RT.sepMixAvg <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + IntraMixingAvg +
IntraMixingAvg*Type + IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c +
InterMixingAvg + InterMixingAvg*Type + InterMixingAvg*Mth_c +
InterMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit,
data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.sepMixAvg)
partR2(RT.sepMixAvg,R2_type="marginal")
partR2(RT.sepMixAvg,R2_type="conditional")
```
- 3.3.2 ACC model: Intra + Inter
```{r model 2-level ACC Intra & Inter model}
ACC.sepMixAvg <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + IntraMixingAvg +
IntraMixingAvg*Type + IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c +
InterMixingAvg + InterMixingAvg*Type + InterMixingAvg*Mth_c +
InterMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit,
family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e6)))
summary(ACC.sepMixAvg)
partR2(ACC.sepMixAvg,R2_type="marginal")
partR2(ACC.sepMixAvg,R2_type="conditional")
```
````

````
## 3.4 Moderatoer: L1 language exposure + Intra
- 3.4.1 RT model: L1 language exposure + Intra
```{r model 2-level RT L1 + Intra model}
RT.L1 <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Percent_L1 + Percent_L1*Type +
Percent_L1*Mth_c + Percent_L1*Type*Mth_c + IntraMixingAvg + IntraMixingAvg*Type +
IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.L1)
partR2(RT.L1,R2_type="marginal")
partR2(RT.L1,R2_type="conditional")
```
- 3.4.2 ACC model: L1 language exposure + Intra
```{r model 2-level ACC L1 + Intra model}
ACC.L1 <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Percent_L1 + Percent_L1*Type +
Percent_L1*Mth_c + Percent_L1*Type*Mth_c + IntraMixingAvg + IntraMixingAvg*Type +
IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.L1)
partR2(ACC.L1,R2_type="marginal")
partR2(ACC.L1,R2_type="conditional")
```
## 3.5 Moderatoer: Language Balance + Intra
- 3.5.1 RT model: Language Balance + Intra
```{r model 2-level RT L1BL + Intra model}
RT.L1BL <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + L1BL + L1BL*Type +
L1BL*Mth_c + L1BL*Type*Mth_c + IntraMixingAvg + IntraMixingAvg*Type +
IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.L1BL)
partR2(RT.L1BL,R2_type="marginal")
partR2(RT.L1BL,R2_type="conditional")
```
- 3.5.2 ACC model: Language Balance + Intra
```{r model 2-level ACC L1BL + Intra model}
ACC.L1BL <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + L1BL + L1BL*Type +
L1BL*Mth_c + L1BL*Type*Mth_c + IntraMixingAvg + IntraMixingAvg*Type +
IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.L1BL)
partR2(ACC.L1BL,R2_type="marginal")
partR2(ACC.L1BL,R2_type="conditional")
```
````

````
# 4. post-hoc analyses
-4.1 RT model
```{r model post-hoc for RT model}
# main effect
emmeans(RT.IntraMixAvg, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(RT.IntraMixAvg, pairwise ~
Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
# Interactions
emmeans(RT.IntraMixAvg, pairwise~Type*IntraMixingAvg,at=list(IntraMixingAvg=c(-
1.59,0,1.59)),pbkrtest.limit = 3231)
emmeans(RT.sepMixAvg, pairwise~Type*Mth_c*IntraMixingAvg,at=list(IntraMixingAvg=c(-
1.59,0,1.59), Mth_c=c(6,10)),pbkrtest.limit = 3231)
```
-4.2 ACC model
```{r model post-hoc for ACC model}
# 1) main effect
emmeans(ACC.IntraMixAvg, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(ACC.IntraMixAvg, pairwise ~
Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
# 2) interactions
emmeans(ACC.IntraMixAvg, pairwise ~
Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
emmeans(ACC.sepMixAvg, pairwise ~
Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
```
````

Bilingual infant only models (including bilingual infants, excluding monolingual & multilingual infants)

````
---
title: "R & R (G)LMM bilingual only (exclude multilingual) - language mixing"
author: "MZhang"
date: "09/10/2021"
output:
  html_document: default
  pdf_document: default
---

```{r package, include=FALSE}
library(psych)
library(scales)
library(lme4)
library(lmerTest)
library(psych)
library(dplyr)
library(ggplot2)
library(emmeans)
library(stringr)
library(partR2)
```

# 1. loading the datafile
- The level-1 data
```{r load the level-1 data}
lvl.one <- read.csv("IBAD_LME_long.csv")
lvl.one <- within(lvl.one, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Trial <- factor(Trial)
  Type <- factor(Block)
  Group <- factor(Grp)
  AdjRT <- AdjRT*1000
  ACC <- factor(Accuracy)
  AdjRT[AdjRT=="NaN"] <- NA
  ACC[ACC=="NaN"] <- NA
})
describe(lvl.one,na.rm=TRUE)
lvl.one.Bi <- lvl.one[which(lvl.one$Grp=="Bi"),]
describe(lvl.one.Bi,na.rm=TRUE)
```
- The level-2 data
```{r load the level-2 data}
lvl.two <- read.csv("IBAD_Cov_wide.csv")
lvl.two <- within(lvl.two, {
````
````

```
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Gender <- factor(Sex)
  MixAvg <- (IntraMixingAvg+InterMixingAvg)/2
  L1BL <- abs(Percent_L1-50) #sd 9.64
  Percent_L1[Percent_L1=="NaN"] <- NA
  Percent_otherL2exp[Percent_otherL2exp=="NaN"] <- NA
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
lvl.two.Bi <- lvl.two[which(lvl.two$LangG=="Bi"),]
describe(lvl.two,na.rm=TRUE)
describe(lvl.two.Bi,na.rm=TRUE)
lvl.two.Bi.only <- lvl.two[which(lvl.two.Bi$MultiG==0),]
describe(lvl.two.Bi,na.rm=TRUE)
data.cor <-
lvl.two.Bi[,c("L1BL","Percent_L1","Percent_otherL2exp","MixingAvg","IntraMixingAvg","Inte
rMixingAvg")]
cor.LM <- cor(data.cor,method="spearman",use="pairwise")
cor.LM
cor.test(data.cor$Percent_L1, data.cor$Percent_otherL2exp)
cor.test(data.cor$Percent_L1, data.cor$IntraMixingAvg)
cor.test(data.cor$Percent_L1, data.cor$InterMixingAvg)
cor.test(data.cor$Percent_otherL2exp, data.cor$IntraMixingAvg)
cor.test(data.cor$Percent_otherL2exp, data.cor$InterMixingAvg)
cor.test(data.cor$L1BL, data.cor$IntraMixingAvg)
cor.test(data.cor$L1BL, data.cor$InterMixingAvg)
cor.test(data.cor$IntraMixingAvg, data.cor$InterMixingAvg)
```

- Merge level-1&2 data

```{r merge level-1&2 data}
data.Bi <- left_join(lvl.one.Bi, lvl.two.Bi,
            by = c("Mth"="Mth","Subj.ID"="Subj.ID"))
data.Bi <- within(data.Bi, {
  MixingAvg <- MixingAvg-4.19 #sd 1.39
  IntraMixingAvg <- IntraMixingAvg-3.86 #sd 1.59
  InterMixingAvg <- InterMixingAvg-4.48 #sd 1.56
  LangP <- Percent_L1 + Percent_otherL2exp
  L1BL <- L1BL-15.18 #sd 9.64
  Percent_L1 <- Percent_L1-66.13 #sd 11.23
```

```
  Percent_otherL2exp <- Percent_otherL2exp-33.41 #sd 11.24
  P_L1 <- Percent_L1/100 #sd 0.1123
  P_L2 <- Percent_otherL2exp/100 #sd 0.1124
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(data.Bi,na.rm=TRUE)
Bi.6 <- data.Bi[which(data.Bi$Mth==6),]
describe(Bi.6,na.rm=TRUE)
Bi.10 <- data.Bi[which(data.Bi$Mth==10),]
describe(Bi.10,na.rm=TRUE)
describe(data.Bi$LangP,na.rm=TRUE)
hist(data.Bi$LangP)
# subsetting to exclude multilinguals (exposed to 3rd/4th languages more than 10%)
data.Bi <- data.Bi[which(data.Bi$MultiG==0),]
describe(data.Bi,na.rm=TRUE)
```

2. build level 1 model

- 2.1 level 1 RT (within-exp level)

```{r model within-exp level RT, include=FALSE}
## null-model
RT.null <- lmer(AdjRT ~ 1 + (1 | Subj.ID), na.action=na.omit, data = data.Bi, REML = FALSE)
summary(RT.null)
## level-1 random intercept
RT.main <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 | Subj.ID), na.action=na.omit, data
= data.Bi, REML = FALSE)
summary(RT.main)
anova(RT.null,RT.main)
## random slope
RT.ranS <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.Bi, REML = FALSE)
summary(RT.ranS)
anova(RT.main,RT.ranS)
```

- 2.2 final-level 1 RT model

```{r model within-exp level FINAL.RT}
RT.within <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + (1 + Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.Bi,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
```

````
summary(RT.within)
partR2(RT.within,R2_type="marginal")
partR2(RT.within,R2_type="conditional")
```
- 2.3 level 1 ACC (within-exp level)
```{r model within-exp level ACC, include=FALSE}
## null-model
ACC.null <- glmer(ACC ~ 1 + (1 | Subj.ID), na.action=na.omit, family = binomial, data =
data.Bi)
summary(ACC.null)
## level-1 random intercept
ACC.main <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + (1 | Subj.ID), na.action=na.omit,
family = binomial, data = data.Bi)
summary(ACC.main)
anova(ACC.null,ACC.main)
## random slope
ACC.ranS <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, family = binomial, data =
data.Bi,control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=1e5)))
summary(ACC.ranS)
anova(ACC.main,ACC.ranS)
```
- 2.4 final-level 1 ACC model
```{r model within-exp level FINAL.ACC}
ACC.within <- ACC.ranS
summary(ACC.within)
partR2(ACC.within,R2_type="marginal")
partR2(ACC.within,R2_type="conditional")
```
# 3. build level-2 model
## 3.1 Moderatoer: Mixing Average
- 3.1.1 RT model: MixAvg
```{r model 2-level RT MA model}
RT.MixAvg <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + MixingAvg + MixingAvg*Type
+ MixingAvg*Mth_c + MixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.MixAvg)
partR2(RT.MixAvg,R2_type="marginal")
partR2(RT.MixAvg,R2_type="conditional")
```
- 3.1.2 ACC model: MixAvg
```{r model 2-level ACC MA model}
ACC.MixAvg <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + MixingAvg + MixingAvg*Type
+ MixingAvg*Mth_c + MixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
````

````
na.action=na.omit, family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.MixAvg)
partR2(ACC.MixAvg,R2_type="marginal")
partR2(ACC.MixAvg,R2_type="conditional")
```
## 3.2 Moderatoer: Intra
- 3.2.1 RT model: Intra
```{r model 2-level RT Intra model}
RT.IntraMixAvg <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + IntraMixingAvg +
IntraMixingAvg*Type + IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type +
Mth_c  + Type*Mth_c | Subj.ID), na.action=na.omit, data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.IntraMixAvg)
partR2(RT.IntraMixAvg,R2_type="marginal")
partR2(RT.IntraMixAvg,R2_type="conditional")
```
- 3.2.2 ACC model: Intra
```{r model 2-level ACC Intra model}
ACC.IntraMixAvg <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + IntraMixingAvg +
IntraMixingAvg*Type + IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type +
Mth_c  + Type*Mth_c | Subj.ID), na.action=na.omit, family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.IntraMixAvg)
partR2(ACC.IntraMixAvg,R2_type="marginal")
partR2(ACC.IntraMixAvg,R2_type="conditional")
```
## 3.3 Moderatoer: Intra + Inter
- 3.3.1 RT model: Intra + Inter
```{r model 2-level RT Intra & Inter model}
RT.sepMixAvg <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + IntraMixingAvg +
IntraMixingAvg*Type + IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c +
InterMixingAvg + InterMixingAvg*Type + InterMixingAvg*Mth_c +
InterMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit,
data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.sepMixAvg)
partR2(RT.sepMixAvg,R2_type="marginal")
partR2(RT.sepMixAvg,R2_type="conditional")
```
- 3.3.2 ACC model: Intra + Inter
```{r model 2-level ACC Intra & Inter model}
ACC.sepMixAvg <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + IntraMixingAvg +
IntraMixingAvg*Type + IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c +
InterMixingAvg + InterMixingAvg*Type + InterMixingAvg*Mth_c +
InterMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit,
````

family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e6)))
summary(ACC.sepMixAvg)
partR2(ACC.sepMixAvg,R2_type="marginal")
partR2(ACC.sepMixAvg,R2_type="conditional")
```
## 3.4 Moderatoer: L1 language exposure + Intra
- 3.4.1 RT model: L1 language exposure + Intra
```{r model 2-level RT L1 + Intra model}
RT.L1 <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Percent_L1 + Percent_L1*Type +
Percent_L1*Mth_c + Percent_L1*Type*Mth_c + IntraMixingAvg + IntraMixingAvg*Type +
IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.L1)
partR2(RT.L1,R2_type="marginal")
partR2(RT.L1,R2_type="conditional")
```
- 3.4.2 ACC model: L1 language exposure + Intra
```{r model 2-level ACC L1 + Intra model}
ACC.L1 <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Percent_L1 + Percent_L1*Type +
Percent_L1*Mth_c + Percent_L1*Type*Mth_c + IntraMixingAvg + IntraMixingAvg*Type +
IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.L1)
partR2(ACC.L1,R2_type="marginal")
partR2(ACC.L1,R2_type="conditional")
```
3.5 Moderatoer: Language Balance + Intra
- 3.5.1 RT model: Language Balance + Intra
```{r model 2-level RT L1BL + Intra model}
RT.L1BL <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + L1BL + L1BL*Type +
L1BL*Mth_c + L1BL*Type*Mth_c + IntraMixingAvg + IntraMixingAvg*Type +
IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c |
Subj.ID), na.action=na.omit, data = data.Bi, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.L1BL)
partR2(RT.L1BL,R2_type="marginal")
partR2(RT.L1BL,R2_type="conditional")
```
- 3.5.2 ACC model: Language Balance + Intra
```{r model 2-level ACC L1BL + Intra model}
ACC.L1BL <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + L1BL + L1BL*Type +
L1BL*Mth_c + L1BL*Type*Mth_c + IntraMixingAvg + IntraMixingAvg*Type +
IntraMixingAvg*Mth_c + IntraMixingAvg*Type*Mth_c + (Type + Mth_c + Type*Mth_c |

````
Subj.ID), na.action=na.omit, family = binomial, data = data.Bi,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.L1BL)
partR2(ACC.L1BL,R2_type="marginal")
partR2(ACC.L1BL,R2_type="conditional")
```
# 4. post-hoc analyses
-4.1 RT model
```{r model post-hoc for RT model}
# 1) main effect + Interactions (save level)
emmeans(RT.MixAvg, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(RT.MixAvg, pairwise ~ Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit =
6077)
emmeans(RT.MixAvg, pairwise ~
Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
# 2) main effect + Interactions (save level)
emmeans(RT.IntraMixAvg, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(RT.IntraMixAvg, pairwise ~
Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
emmeans(RT.IntraMixAvg, pairwise ~
Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
# Interactions
emmeans(RT.MixAvg, pairwise~Type*MixingAvg,at=list(MixingAvg=c(-
1.39,0,1.39)),pbkrtest.limit = 3231)
emmeans(RT.IntraMixAvg, pairwise~Type*IntraMixingAvg,at=list(IntraMixingAvg=c(-
1.59,0,1.59)),pbkrtest.limit = 3231)
emmeans(RT.sepMixAvg, pairwise~Type*IntraMixingAvg,at=list(IntraMixingAvg=c(-
1.59,0,1.59)),pbkrtest.limit = 3231)
```
-4.2 ACC model
```{r model post-hoc for ACC model}
# 1) main effect
emmeans(ACC.MixAvg, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(ACC.MixAvg, pairwise ~ Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit =
6077)
emmeans(ACC.MixAvg, pairwise ~
Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
# 2) main effect
emmeans(ACC.IntraMixAvg, pairwise ~ Type,lmerTest.limit = 6077)
emmeans(ACC.IntraMixAvg, pairwise ~
Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
emmeans(ACC.IntraMixAvg, pairwise ~
Type*Mth_c,var="Mth_c",at=list(Mth_c=c(6,10)),pbkrtest.limit = 6077)
```
````
````

Larger sample models with covariates (e.g., infant sex, parental education)

```
---
title: "R & R (G)LMM whole sample - language group + covariates"
author: "MZhang"
date: "09/10/2021"
output:
  html_document: default
  pdf_document: default
---

```{r package, include=FALSE}
library(psych)
library(scales)
library(lme4)
library(lmerTest)
library(psych)
library(dplyr)
library(ggplot2)
library(emmeans)
library(stringr)
library(partR2)
library(e1071)
```

1. loading the datafile
- The level-1 data
```{r load the level-1 data}
lvl.one <- read.csv("IBAD_LME_long.csv")
lvl.one <- within(lvl.one, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Trial <- factor(Trial)
  Type <- factor(Block)
  Group <- factor(Grp)
  AdjRT <- AdjRT*1000
  ACC <- factor(Accuracy)
  AdjRT[AdjRT=="NaN"] <- NA
  ACC[ACC=="NaN"] <- NA
})
describe(lvl.one,na.rm=TRUE)
skewness(lvl.one$AdjRT,na.rm=TRUE)
kurtosis(lvl.one$AdjRT,na.rm=TRUE)
hist(lvl.one$AdjRT)
```
- The level-2 data
```{r load the level-2 data}
```
```

~~~
lvl.two <- read.csv("IBAD_Cov_wide.csv")
lvl.two <- within(lvl.two, {
  Subj.ID <- str_sub(Subject.ID,1,-7)
  Sex <- factor(Sex)
  MixAvg <- (IntraMixingAvg+InterMixingAvg)/2
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
table(lvl.two$Sex,lvl.two$LangG)
chisq.test(lvl.two$Sex,lvl.two$LangG, correct=TRUE)
chisq.test(x=c(85,98), p=c(1/2,1/2)) #gender
chisq.test(x=c(97,86), p=c(1/2,1/2)) #language group
describe(lvl.two,na.rm=TRUE)
```
- Merge level-1&2 data
```{r merge level-1&2 data}
data.2lvl <- left_join(lvl.one, lvl.two,
            by = c("Mth"="Mth","Subj.ID"="Subj.ID"))
data.2lvl <- within(data.2lvl, {
  AvgPEduc <- AvgPEduc - 3.19 #sd = 0.89
  AvgPEduc[AvgPEduc=="NaN"] <- NA
  MixingAvg[MixingAvg=="NaN"] <- NA
  InterMixingAvg[InterMixingAvg=="NaN"] <- NA
  IntraMixingAvg[IntraMixingAvg=="NaN"] <- NA
  Inter1[Inter1=="NaN"] <- NA
  Inter2[Inter2=="NaN"] <- NA
  Intra1[Intra1=="NaN"] <- NA
  Intra2[Intra2=="NaN"] <- NA
  MixingSubjScoreItem[MixingSubjScoreItem=="NaN"] <- NA
})
describe(data.2lvl,na.rm=TRUE)
data.2lvl.m <- data.2lvl[data.2lvl$Sex=="M",]
data.2lvl.f <- data.2lvl[data.2lvl$Sex=="F",]
describe(data.2lvl.m,na.rm=TRUE)
describe(data.2lvl.f,na.rm=TRUE)
```
# 2. build level 3 model (include langauge group as a moderator)
- 2.1 Male
- 2.1.1 RT model: male
~~~

```{r model 2-level RT male model, include=FALSE}
RT.male <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, data = data.2lvl.m, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.male)
partR2(RT.male,R2_type="marginal")
partR2(RT.male,R2_type="conditional")
```
- 2.1.2 ACC model: male
```{r model 2-level ACC male model, include=FALSE}
ACC.male <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, family = binomial, data = data.2lvl.m,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.male)
partR2(ACC.male,R2_type="marginal")
partR2(ACC.male,R2_type="conditional")
```
- 2.2 Female
- 2.2.1 RT model: female
```{r model 2-level RT female model, include=FALSE}
RT.female <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, data = data.2lvl.f, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.female)
partR2(RT.female,R2_type="marginal")
partR2(RT.female,R2_type="conditional")
```
- 2.2.2 ACC model: female
```{r model 2-level ACC female model, include=FALSE}
ACC.female <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID),
na.action=na.omit, family = binomial, data = data.2lvl.f,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.female)
partR2(ACC.female,R2_type="marginal")
partR2(ACC.female,R2_type="conditional")
```
3. add covariate
3.1 gender
- 3.1.1 RT: gender
```{r model 2-level RT-sex model}
RT.sex <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Group + Group*Type + Group*Mth_c
+ Group*Type*Mth_c + Sex + Type*Sex + Mth_c*Sex + Sex*Type*Mth_c + (Type + Mth_c +
```

````
Type*Mth_c | Subj.ID), na.action=na.omit, data = data.2lvl, REML = TRUE,
control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.sex)
partR2(RT.sex,R2_type="marginal")
partR2(RT.sex,R2_type="conditional")
```
- 3.1.2 ACC: gender
```{r model 2-level ACC-sex model}
ACC.sex <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + Sex + Type*Sex + Mth_c*Sex + Sex*Type*Mth_c +
(Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit, family = binomial, data = data.2lvl,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.sex)
partR2(ACC.sex,R2_type="marginal")
partR2(ACC.sex,R2_type="conditional")
```
## 3.2: parent education
- 3.2.1 RT: parent education
```{r model 2-level RT-peduc model}
RT.peduc <- lmer(AdjRT ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + AvgPEduc + Type*AvgPEduc + Mth_c*AvgPEduc +
AvgPEduc*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit, data =
data.2lvl, REML = TRUE, control=lmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(RT.peduc)
partR2(RT.peduc,R2_type="marginal")
partR2(RT.peduc,R2_type="conditional")
```
- 3.2.2 ACC: parent education
```{r model 2-level ACC-peduc model}
ACC.peduc <- glmer(ACC ~ Type + Mth_c + Type*Mth_c + Group + Group*Type +
Group*Mth_c + Group*Type*Mth_c + AvgPEduc + Type*AvgPEduc + Mth_c*AvgPEduc +
AvgPEduc*Type*Mth_c + (Type + Mth_c + Type*Mth_c | Subj.ID), na.action=na.omit, family
= binomial, data = data.2lvl,
control=glmerControl(optimizer="bobyqa",optCtrl=list(maxfun=2e5)))
summary(ACC.peduc)
partR2(ACC.peduc,R2_type="marginal")
partR2(ACC.peduc,R2_type="conditional")
```
````
````