The Development of Gaze Following in Monolingual and Bilingual Infants: A Multi-Lab Study

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31   Abstract

32   Determining the meanings of words requires language learners to attend to what other

33   people say. However, it behooves a young language learner to simultaneously attend to what

34   other people attend to, for example, by following the direction of their eye gaze. Sensitivity

35   to cues such as eye gaze might be particularly important for bilingual infants, as they

36   encounter less consistency between words and objects than monolinguals, and do not always

37   have access to the same word learning heuristics (e.g., mutual exclusivity). In a

38   pre-registered study, we tested the hypothesis that bilingual experience would lead to a more

39   pronounced ability to follow another's gaze. We used the gaze-following paradigm developed

40   by Senju & Csibra (2008) to test a total of 93 6–9 month-old and 229 12–15 month-old

41   monolingual and bilingual infants, in 11 labs located in 8 countries. Monolingual and

42   bilingual infants showed similar gaze-following abilities, and both groups showed age-related

43   improvements in speed, accuracy, frequency and duration of fixations to congruent objects.

44   Unexpectedly, bilinguals tended to make more frequent fixations to onscreen objects,

45   whether or not they were cued by the actor. These results suggest that gaze sensitivity is a

46   fundamental aspect of development that is robust to variation in language exposure.

47   *Keywords:* gaze following, bilingualism, infancy, replication, reproducibility, age-related

48   changes

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Study

Bilingual infants face the remarkable task of acquiring two languages simultaneously. Bilinguals show developmental adaptations to their unique environments, which might support their observed success in learning their two languages (Werker & Byers-Heinlein, 2008). In comparison to monolinguals, bilingual infants show differences in early speech perception (Byers-Heinlein & Fennell, 2014), in word learning (Fennell, Byers-Heinlein, & Werker, 2007; Graf Estes & Hay, 2015; Singh, Fu, Tay, & Golinkoff, 2018), and in acquisition of grammatical structures (Antovich & Graf Estes, 2018; Kovács & Mehler, 2009b). They show different patterns of looking towards talking faces (Pons, Bosch, & Lewkowicz, 2015), and are more sensitive to facial cues that discriminate speakers of different languages (Sebastián-Gallés, Albareda-Castellot, Weikum, & Werker, 2012; Weikum et al., 2007). These differences have been attributed to specific features of bilingual environments that may influence developing cognitive processes. Specifically, the notion that bilingual infants attend to and learn two languages is thought to sharpen their capacity to flexibly switch between their languages (Antovich & Graf Estes, 2018; Kandhadai, Danielson, & Werker, 2014; Kovács & Mehler, 2009a) and to acquire the individual properties of two language systems (Kovács & Mehler, 2009b). Moreover, as bilingual infants typically encounter less single-language input than their monolingual peers, new information may be encoded with increased efficiency and detail (Brito & Barr, 2014; Liu & Kager, 2016; Singh et al., 2015). These findings suggest that, before infants begin to produce words in their native language(s), immersion in a bilingual environment modifies the development of some aspects of infants' perception and learning.

More intriguingly, bilingualism also appears to impact abilities that do not directly involve language. For example, relative to monolinguals, bilingual infants are more likely to inhibit recently learned information (Kovács & Mehler, 2009a), generalize across visual

75 features when categorizing objects (Brito & Barr, 2014), and encode and retrieve visual

76 information (Singh et al., 2015). Here, we ask whether bilingual infants also show enhanced

77 sensitivity to non-linguistic social information, a question that has thus far received very

78 little attention. In an international, multi-site study, we investigated whether the ability to

79 follow a social partner's eye gaze follows the same developmental trajectory in monolingual

80 and bilingual infants, and found overall no major differences in infants' eye gaze following as

81 a function of language background.

The development of gaze following

83   Infants show an early-emerging sensitivity to a social partner's eye gaze. In a primitive

84 form, very young infants are sensitive to the direction of a speaker's gaze, attending to visual

85 targets more rapidly when they are cued by an adult's gaze (Farroni, Massaccesi, Pividori, &

86 Johnson, 2004; Reid, Striano, Kaufman, & Johnson, 2004). Throughout the first year and a

87 half of life, infants refine their interpretation of eye and head movements: they distinguish

88 between head-turns with open versus closed eyes (Brooks & Meltzoff, 2005), become able to

89 follow changes in gaze unaccompanied by a head turn (Corkum & Moore, 1995; Moore &

90 Corkum, 1998), and attend to whether another's gaze is obscured from view by a physical

91 barrier (Meltzoff & Brooks, 2007). In sum, over the course of infancy, infants progress from

92 attending to the direction of the eyes, to engaging in gaze following in a more selective

93 fashion, to true gaze following where the actions of a social partner are interpreted as

94 intentional and informative (Brooks & Meltzoff, 2014; Frischen, Bayliss, & Tipper, 2007;

95 Moore, 2008).

96   A number of recent studies have highlighted the situations that most reliably elicit

97 gaze following in infancy. As an example, Senju & Csibra (2008) investigated gaze-following

98 abilities of 6-month-old infants. This age is of particular interest as it corresponds to the

99 onset of word comprehension (Bergelson & Swingley, 2012; Fenson et al., 2007). An adult

model sat in between two toys, one located to her left and one to her right. Infants were tested in one of two conditions. In the Eye Contact condition by Senju & Csibra (2008) the model looked into the camera, thus potentially making eye contact with the infant, and then directed her gaze at one of the toys. In the No Eye Contact condition, the model initially looked down instead of towards the infant, and a superimposed animation drew the infant's attention to her head. Results revealed that infants followed the model's gaze in the Eye Contact condition, but not in the No Eye Contact condition. In a replication and extension of Senju & Csibra (2008)'s paradigm, Szufnarowska, Rohlfing, Fawcett, & Gredebäck (2014) demonstrated that 6-month-old infants responsively followed an adult's gaze similarly when it was preceded by attention-grabbing behaviors without eye contact, such as shivering or nodding. This suggests that the ability for eye gaze to elicit gaze following behavior may be partially related to its attentional draw.

Several studies have used the paradigm developed by Senju & Csibra (2008) to explore how infants' individual experiences with gaze affect their gaze-following abilities. For example, one study investigated gaze following in sighted infants of blind parents (Senju et al., 2013). These infants showed a similar ability to follow the gaze of a sighted social partner as infants of sighted parents, despite having less experience with gaze behaviors. Another study looked at gaze following in infants at risk for communicative impairments (Bedford et al., 2012). Although both at-risk and low-risk infants were equally likely to follow an adult's gaze, at-risk 13-month-olds spent less total time looking at objects to which an adult's gaze was directed. This suggested that they might have been less able to make use of gaze as a socially relevant cue than typically developing infants. Together, these studies suggest that gaze following is an ability that develops across varied developmental circumstances, although the results from at-risk infants show that the use of gaze information can differ across populations. Importantly, these studies provide support for the use of Senju & Csibra (2008)'s task, which has elicited gaze following across studies and populations.

Gaze following in bilinguals

One group of infants that might differ in the development of gaze-following abilities is bilingual infants, although no study to date has specifically tested this group. There are several reasons to posit that bilinguals may demonstrate increased attention to gaze patterns of social partners. One reason is that gaze following is not only an important social skill, but it also contributes to early language learning. Language is a highly social system of communication. Speakers often look towards their intended referent. Thus the ability to follow a conversational partner's gaze can guide children in correctly mapping words to objects, and help to resolve the problem of referential ambiguity (Baldwin, 1995; Brooks & Meltzoff, 2002; Tomasello, 2003; Woodward, 2003). Many theories of language acquisition emphasize the influence of social cues in the search for meaning, proposing that infants' sensitivity to social cues scaffolds accurate and efficient vocabulary development (Baldwin, 1995; Bloom, 2000; Hollich et al., 2000; Mundy, Sullivan, & Mastergeorge, 2009; Tomasello, 2003). There is substantial empirical support for this theoretical stance: infant gaze following is both concurrently and predictively related to word learning (e.g., Brooks & Meltzoff, 2005, 2008; Carpenter, Nagell, & Tomasello, 1998; Morales et al., 2000; Mundy et al., 2007; Paulus & Fikkert, 2014; Tenenbaum, Sobel, Sheinkopf, Malle, & Morgan, 2015).

The ability to use gaze information in language learning might be particularly important for bilingual infants. Bilingual infants' experiences are divided between their two languages, and they must learn two labels for each object (one in each language). When a monolingual English-learning infant encounters an object such as an apple, they will consistently hear the word "apple" to refer to that object. However, when a French-English bilingual encounters the same object, they will sometimes hear the English word "apple" and sometimes hear the French word "pomme". For bilinguals, there may be less consistency in object-label correspondences. Unlike monolinguals, they eventually have to map at least two labels to each object (one in each language).

¹⁵²   The need to map multiple labels onto the same object may make some of the word

¹⁵³ learning strategies used by monolingual learners less useful for bilingual learners. Both

¹⁵⁴ groups should share basic assumptions about the relationship between words and objects

¹⁵⁵ that can support word learning, like the assumption that words refer to whole objects rather

¹⁵⁶ than their parts, and that a new word should be extended to other objects of the same kind

¹⁵⁷ (Markman, 1990). However, one key assumption that may differ across monolinguals and

¹⁵⁸ bilinguals is mutual exclusivity, the assumption that each object has a unique label

¹⁵⁹ (Markman & Wachtel, 1988). Mutual exclusivity allows monolinguals to reject objects with a

¹⁶⁰ known label as a referent for a novel word. Strict use of such a heuristic would be less useful

¹⁶¹ to bilingual learners, as they must learn two labels for each object. Indeed, evidence from

¹⁶² bilingual infants at age 9 months (Byers-Heinlein, 2017) and 17–18 months (Byers-Heinlein

¹⁶³ & Werker, 2009, 2013; Houston-Price, Caloghiris, & Raviglione, 2010) indicates that

¹⁶⁴ bilinguals do not assume that each object has only one label, and are less likely to use word

¹⁶⁵ learning heuristics such as mutual exclusivity. If mutual exclusivity is less available to

¹⁶⁶ bilingual word learners, then they might need to more strongly rely on other cues to word

¹⁶⁷ meaning such as eye gaze.

¹⁶⁸   Another important monolingual-bilingual difference is that bilingual learners receive

¹⁶⁹ less input in each language in comparison to monolingual learners. While this might be

¹⁷⁰ expected to delay word learning, bilingual infants comprehend and produce their first words

¹⁷¹ on largely the same schedule as monolingual infants (De Houwer, Bornstein, & De Coster,

¹⁷² 2006; Petitto et al., 2001). Moreover, when vocabulary in both languages is considered,

¹⁷³ monolinguals and bilinguals have similar vocabulary sizes (Core, Hoff, Rumiche, & Señor,

¹⁷⁴ 2013; Pearson, Fernández, & Oller, 1993). Thus, bilinguals appear to have a similar rate of

¹⁷⁵ vocabulary development despite reduced frequency of exposure to particular words (although

¹⁷⁶ see Bilson, Yoshida, Tran, Woods, & Hills, 2015, for a different perspective). This could

¹⁷⁷ imply that bilinguals are adept at leveraging other sources of information for word learning,

¹⁷⁸ such as eye gaze, which could offset the effects of reduced single-language input.

There is some evidence from older children to support the hypothesis that bilingual infants have an enhanced ability to follow a social partner's gaze. For example, when object cues and eye gaze cues to meaning were pitted against one another, 2- to 3-year-old bilinguals weighed eye gaze cues more heavily than monolinguals to identify the referent of a newly learned word (Brojde, Ahmed, & Colunga, 2012). In a similar study, Yow & Markman (2011) demonstrated that 2- to 4-year-old bilingual children made greater use of eye gaze than monolingual peers to locate a hidden object. This effect was observed only under challenging circumstances in which the experimenter was seated at a distance from the referent and closer to a competing distractor object. In a study investigating children's use of eye gaze to map novel words to referents and additionally, to infer the meanings of other words via mutual exclusivity, Yow et al. (2017) found that 4- to 5-year-old bilingual children made greater use of eye gaze to identify word-meaning links that were directly taught as well as those that were identifiable via mutual exclusivity.

Together, these studies provide evidence that preschool-aged bilingual children are more adept than monolinguals at using eye gaze cues in word learning contexts. This raises the possibility that bilinguals might also show enhanced sensitivity to a social partner's eye gaze even earlier in development than monolinguals.

A multi-lab collaborative study

We conducted a multi-lab collaborative study to investigate whether infants' language background can influence the development of gaze following. Multi-lab collaborative studies, which involve data collection across multiple sites to generate a large-scale data set, offer several promises for infant research. This approach allows us to increase the diversity and the size of the sample than can be collected in a single laboratory, protecting against incorrect conclusions due to sampling error. Moreover, comparisons across labs can speak to the generalizability of results. For example, such an approach could clarify whether any

204 observed monolingual-bilingual differences generalize across different samples and could

205 reveal whether any observed effects are likely due to bilingualism per se or could be

206 attributed to other sample characteristics, for example, the specific language or cultural

207 context. Within infant bilingualism research, very few studies have collected data from

208 multiple groups of monolingual and bilingual infants on the same task, and cross-cultural

209 comparisons on infant bilingual development are entirely absent.

210   There are many methodological challenges faced in conducting research with bilinguals,

211 particularly in infancy, that motivate using a multi-lab collaborative approach. Many of

212 these challenges are inherent to the nature of the population, and make it difficult to know

213 whether and how findings from one population of bilinguals generalize to other populations.

214 First, while the term "bilingual" can be used for any infant who is exposed to two or more

215 languages, bilingual infants vary in the particular language pair they are learning. Some

216 studies have included only groups of homogeneous bilinguals (i.e., infants exposed to the

217 same pair of languages, such as Spanish-Catalan), while others have included heterogeneous

218 bilinguals (i.e., infants exposed to different pairs of languages, having one language in

219 common, for example, English-Japanese, English-Spanish, English-French). Different

220 language combinations could present different language-learning challenges. While our study

221 was not designed to tease apart the role of particular language pairings (although our data

222 do allow us to explore this issue in a preliminary way), it will establish the generalizability of

223 findings across different groups of bilinguals.

224   Second, given the continuous nature of language exposure, it is challenging to validly

225 and consistently define what makes an infant "monolingual" versus "bilingual". Specifically,

226 few infants are exposed to their two languages in an exactly equal proportion. Instead, the

227 amount of exposure to each of their languages can vary enormously, and there is not always

228 consensus about how much exposure is necessary to acquire a language. As a result, different

229 studies have defined bilingualism differently: while in some studies 10% exposure to the

230 non-dominant language was enough for infants to be considered bilingual, other studies

231 required at least 40% of exposure (Byers-Heinlein, 2015), although 25% is a commonly-used

232 cutoff. An additional complication is that the onset of exposure to any additional languages

233 is highly variable, and could be as early as birth or anytime thereafter. Published studies

234 differ with respect to whether strict or relaxed inclusion requirements are set for the onset of

235 exposure to different languages. A benefit of this collaborative approach is that there is a

236 consistent definition of exposure across participating laboratories.

237   Finally, bilingualism cannot be randomly assigned. Thus, even when recruited from the

238 same geographic region, monolingual and bilingual populations often differ systematically in

239 culture or socio-economic status. Such confounds can make it difficult to determine whether

240 bilingualism itself, rather than another correlated variable, drives observed

241 monolingual–bilingual differences. While such factors can be statistically controlled, these

242 confounds can raise issues about the validity of conclusions and the replicability of the

243 results in bilingualism research. In particular, a number of reports have suggested that

244 long-standing beliefs about the cognitive effects of bilingualism may not be as robust as

245 previously assumed (de Bruin, Treccani, & Della Sala, 2015; Duñabeitia & Carreiras, 2015;

246 Paap, Johnson, & Sawi, 2015; see also Klein, 2015). Indeed, such issues are of increasing

247 concern in the wider field of psychology, where there are ongoing concerns about the

248 replicability of psychological research in general (see Ioannidis, 2012), and specifically about

249 the cross-cultural replicability of basic psychological phenomena thought to be universal

250 (Henrich, Heine, & Norenzayan, 2010). Concerns about the replicability and generalizability

251 of research findings are particularly acute in the field of infant research, where single-lab

252 studies tend to have small sample sizes, high variability, and use indirect experimental

253 measures (see Frank et al., 2017, for a detailed discussion of these issues). Multi-lab studies

254 can go further than single-lab studies to address many of these issues. Characteristics that

255 are idiosyncratic to a particular sample will average out to some degree in a multi-lab study

256 that includes samples from multiple cultures and language backgrounds. Our approach of

comparing gaze following in monolinguals and bilinguals growing up in different contexts, tested across multiple labs, provides important information about the replicability and generalizability of the effects we observe.

Current study

The current study used a multi-lab approach to ask whether monolingual and bilingual infants differ in their basic gaze-following abilities. Data were collected from 11 labs in 8 countries. We tested the hypothesis that the challenging nature of bilingual language-learning environments enhances bilingual infants' attention to the eye gaze of a social partner, even in non-linguistic situations. Our study compared monolingual and bilingual infants aged 6–9 and 12–15 months using the eye gaze stimuli from Senju & Csibra (2008)'s study. Note that our study did not include the No Eye Contact condition reported in Senju and Csibra's paper, as our interest was in comparing gaze-following behavior in typical situations, across infants from different language backgrounds. On six test trials, infants saw a model look towards the camera, and then direct her head and eyes towards one of two objects located to her left and right. We measured the latency and accuracy of infants' gaze following.

Previous studies have found that infants follow the actor's gaze in this condition at above-chance level by 6 months, but their performance is not always reliable (Senju & Csibra, 2008; Szufnarowska et al., 2014). Moreover, there is evidence for improvement of infants' gaze following in this paradigm from 7 to 13 months (Bedford et al., 2012). We thus expected to see improvement in all infants' gaze following from the younger age to the older age. We also expected that both groups would demonstrate successful gaze following as demonstrated by Senju & Csibra (2008), but that bilingual infants would show faster and more accurate gaze following than monolingual infants. We also suggest that the effects of bilingualism might interact with age. On the one hand, we might observe a stronger effect of bilingualism at 6–9 months if gaze following emerges earlier for bilinguals; on the other hand

we might observe a stronger effect of bilingualism at 12–15 months if this skill emerges at the same age, but is more relied upon by bilingual infants as the demands of language acquisition increase. Both of these findings would reflect interesting and meaningful differences between monolingual and bilingual infants.

Methods

We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. The present study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board or Ethics Committee at each lab's respective institution.

Participation Details

Time frame. An open call for labs to participate was issued on March 14, 2017. Participant testing began on July 1, 2017 and ended on August 31, 2018.

Age and language groups. Labs contributed samples from one or both of two possible age bins: 6–9 months (184–274 days) and 12–15 months (366–456 days). Labs were asked to aim for a mean age at the centre of each bin, with distribution across the entire age window. Labs could contribute a monolingual and/or bilingual sample at one or both ages (see below for inclusion criteria for monolingual and bilingual groups).

Lab participation. Considering the challenges associated with recruiting bilingual infants and the importance of counterbalancing in our experimental design, we asked labs to contribute a minimum of 16 healthy, full-term infants per age (6–9, 12–15) and language group (monolingual, bilingual). However, labs were encouraged to contribute data even if

305 they were only able to provide a bin of data for a single age or for a single language group.

306 Further, labs were invited to contribute additional data provided that decisions about when

307 to stop data collection were made without looking at the data, to avoid biasing effect sizes.

308 Labs were asked to screen ahead of time that infants met inclusion criteria. However, it was

309 acknowledged that most labs would end up recruiting infants who did not necessarily meet

310 our pre-defined criteria for bilingualism (detailed below) upon more detailed in-lab language

311 background assessment. In such cases, the decision whether to test the infant was left up to

312 individual laboratories' policies, but we asked that data from any babies who entered the

313 testing room be submitted for data processing (even though some such data might be

314 excluded from the main analyses). Eleven labs contributed at least one data bin.

315   Nine of the 11 participating labs were also participating in two prior multi-lab

316 collaborative studies (ManyBabies 1 study and/or ManyBabies 1 Bilingual study)

317 investigating infants' preference for infant-directed speech (Byers-Heinlein, Tsui, et al., 2020;

318 ManyBabies Consortium, 2020). The current study emerged out of the unique opportunity

319 afforded by a significant number of labs with a bilingual population coming together to run

320 the Manybabies 1 Bilingual study, and the desire to make optimal use of these resources. As

321 such, prior to completing the current study, 42.88% of the infants completed the ManyBabies

322 1 study on the same visit in the lab. Testing infants in two different studies on the same visit

323 is a common practice in many, although not all, infant labs. We note that these two studies

324 adopted different designs (listening preference vs. gaze following), and tracked sensitivity to

325 different sorts of cues (auditory vs. visual). Moreover, the current study (gaze following)

326 presented infants with engaging social stimuli and was short in duration. These features

327 mitigated possible carryover effects.

328   **Power analysis.** In their paper, Senju & Csibra (2008) report a comparison against

329 chance of $t(18) = 2.74$ in our target condition (the Eye Contact condition of Experiment 2),

330 yielding a calculated effect size of Cohen's $d = 1.29$ for infants of this age for the first look

measure. This would necessitate a sample size of only 6 infants to have an 80% chance of detecting a significant difference in a single-sample t-test. With our planned sample size of 16 infants/group per lab, power within each lab to detect this effect will be .94.

However, our primary hypothesis concerned the comparison of monolingual and bilingual infants. Because this is the first study to investigate this question, it is difficult to know what effect size might be expected in this comparison. We thus conducted a sensitivity analysis, setting target power at .8 and alpha at .05. For individual labs to detect a statistically significant difference between monolinguals and bilinguals (n = 16 infants per group) in an independent samples t-test, we would need to observe a large effect size of Cohen's $d = 1.0$. However, collapsing across the labs (projected to be approximately 100 monolinguals and bilinguals per age group for a total sample of 400), we would be able to detect a small to medium effect size of Cohen's $d = .28$ at either age. Conducting multiple regression models with 3–6 predictors (see analytic plan) with the data from all labs across both age groups, we would be able to detect statistically significant contribution(s) from between one (e.g., bilingualism) and three (e.g., bilingualism, age, and their interaction) predictors with a small effect size in the range of Cohen's $f^2 = .019$–.028. Thus, we felt confident that our design would have sufficient statistical power to detect a difference between monolinguals and bilinguals that was small to medium in magnitude.

Ethics. The present study was conducted according to the Declaration of Helsinki guidelines, with written informed consent obtained from a parent or guardian for each child before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board at the institutions where data was collected. Each lab followed the ethical guidelines and ethics review board protocols of their own institutions. Labs submitted anonymized data for central analysis that identified participants by code only. Data from individual participants were coded and stored locally at each lab, and, where possible, were uploaded to a central controlled-access databank

357 accessible to other researchers.

358 **Participants**

359   **Classification of participants into language groups.**   As in previous studies,

360 infants were categorized as bilingual or monolingual according to parent estimates of

361 language input to their child. Infants were classified as monolingual if they heard the

362 community language at least 90% of the time. There is some variation across studies in how

363 much exposure to the non-dominant language is typically required for infants to be classified

364 as bilingual, with a range of values from 10% to 40% (Byers-Heinlein, 2015). A widely

365 accepted criterion is a range of a minimum exposure estimate of 25% and maximum

366 exposure of 75% to each language, which served as a recruitment guideline for the present

367 study. Thus, our bilingual sample included infants who heard their community language

368 (e.g., the language learned by most monolinguals in their community) at least 25% of the

369 time and an additional language at least 25% of the time. Infants with exposure to a third

370 or fourth language were included as long as they met this criterion. We also asked labs to

371 limit their sample to simultaneous bilingual infants, who heard both languages regularly

372 from within the first month of life. Infants who did not meet inclusion criteria for either

373 group (for example, an infant with 85% exposure to one language, and 15% exposure to

374 another, or who began learning a second language at age 6 months) could be tested if they

375 inadvertently arrived in the lab, according to each lab's policy. However, their data were not

376 included in the main sample, but were retained for further exploratory analysis. Each

377 laboratory was asked to recruit a sample of bilingual infants who received exposure to the

378 community language as one of their languages and to recruit monolingual infants exposed to

379 the community language. As a result, some samples consisted of heterogeneous bilinguals

380 and others of homogenous bilinguals.

381   Each laboratory was asked to administer their own adaptation of a day-in-the-life

parental interview asking about proportionate exposure to each language, which were typically based on the approach developed by Bosch & Sebastián-Gallés (2001). As laboratories often customize questionnaires to suit their local environment, it was concluded that each laboratory would be best able to decide on the variation of the language exposure tool that was optimal for their participant population. As some participating laboratories had not collected bilingual data prior to the study, these laboratories were paired with laboratories more experienced in infant bilingualism research to receive support and guidance in selecting or adapting a suitable language exposure questionnaire.

Although adapted for their language environment by each lab, there is consistency in the information sought from different versions of the language exposure questionnaire. Specifically, each adaptation walks parents through a "day-in-the-life" of their infant, asking about routines, caregivers, and the languages that they speak. An interviewer notes how much each language is spoken to the child during weekdays, weekends, and at different points of the infants' life from caregivers. Indirect exposure through media such as television and radio, as well as overhead speech, are typically excluded (Byers-Heinlein, 2015). Together, this information is used to calculate the total percentage that the infant is directly exposed to each language.

Demographics.   Each lab administered a questionnaire that gathered basic demographic data about infants, including age, health history, gestation, etc.

Final sample.   Our final sample of bilinguals included 131 infants tested in 9 labs. 45 were 6–9 months, and 86 were 12–15 months old. Each of these labs also collected data from monolingual infants (N = 149), of whom 30 were 6–9 months, and 119 were 12–15 months. Data from monolingual infants were available from two additional labs (N = 42), who did not contribute bilingual data. A list of monolingual and bilingual populations in each lab are reported in Table 1. In addition, 2 labs registered to participate but failed to collect data from at least 10 included infants, and so their data were not included.

408 Information about all included labs is given in Table 1.

Table 1

Statistics of the included labs. N refers to the number of infants included in the final analysis.

Lab	Age group	Lang group	Mean age (days)	N	Method
babylab-brookes	12–15 mo	bilingual	394	15	eye-tracking
babylab-brookes	12–15 mo	monolingual	415	14	eye-tracking
babylab-brookes	6–9 mo	bilingual	242	8	eye-tracking
babylab-brookes	6–9 mo	monolingual	238	8	eye-tracking
babylab-princeton	12–15 mo	monolingual	421	14	hand-coding
babylab-princeton	6–9 mo	bilingual	239	9	hand-coding
cdc-ceu	12–15 mo	bilingual	420	11	eye-tracking
cdc-ceu	12–15 mo	monolingual	404	10	eye-tracking
elp-georgetown	12–15 mo	bilingual	416	4	eye-tracking
elp-georgetown	12–15 mo	monolingual	425	7	eye-tracking
elp-georgetown	6–9 mo	bilingual	260	4	eye-tracking
elp-georgetown	6–9 mo	monolingual	242	5	eye-tracking
infantlanglab-utk	12–15 mo	monolingual	408	15	hand-coding
infantlanglab-utk	6–9 mo	monolingual	239	13	hand-coding
irl-concordia	12–15 mo	bilingual	403	14	eye-tracking
irl-concordia	12–15 mo	monolingual	399	16	eye-tracking
irl-concordia	6–9 mo	bilingual	235	11	eye-tracking
irl-concordia	6–9 mo	monolingual	214	7	eye-tracking
koku-hamburg	12–15 mo	monolingual	419	9	eye-tracking
koku-hamburg	6–9 mo	monolingual	234	5	eye-tracking
lll-liv	12–15 mo	bilingual	390	7	eye-tracking
lll-liv	12–15 mo	monolingual	400	15	eye-tracking
lll-liv	6–9 mo	bilingual	235	7	eye-tracking
lll-liv	6–9 mo	monolingual	230	8	eye-tracking
nusinfantlanguagecentre	12–15 mo	bilingual	426	4	hand-coding, eye-tracking
nusinfantlanguagecentre	12–15 mo	monolingual	416	6	hand-coding, eye-tracking

nusinfantlanguagecentre	6–9 mo	bilingual	261	6	eye-tracking
nusinfantlanguagecentre	6–9 mo	monolingual	246	2	eye-tracking, hand-coding
upf_barcelona	12–15 mo	bilingual	414	7	eye-tracking
upf_barcelona	12–15 mo	monolingual	404	11	eye-tracking
weltentdecker-zurich	12–15 mo	bilingual	408	24	eye-tracking
weltentdecker-zurich	12–15 mo	monolingual	416	26	eye-tracking

Stimuli

Stimuli consisted of videos of a female actor sitting at a table, directing her gaze to one of two colorful toys. Each video had the following sequence: the video began with the actor looking straight ahead for 1 second. She looked down for two seconds, after which a beep sounded to attract infants' attention prior to the actor directing her gaze to a toy. Upon presentation of the beep, the actor looked up at the camera and, maintaining a neutral expression, she raised her eyebrows. Four seconds into the video, she began to turn her head towards the left or right and gazed towards the toy in her line of sight until the end of the video. There were a total of 24 different videos in this style, using six different pairs of colourful objects. Video presentations were counterbalanced for the side of presentation of the objects and the object at which the actor gazed, and arranged such that there were six test trials per infant. Original movies were in .avi format, exported at a framerate of 25 frames/second. Each movie lasted a total of 10 seconds (250 frames).

Procedure

We replicated the Eye Contact condition of Experiment 1 from Senju & Csibra (2008), using the original stimuli provided by the authors. Infants were seated on their parents' laps in a quiet, dimly lit testing booth. Caregivers and infants were seated facing a monitor. The caregiver wore an occluder (e.g., sleep mask or opaque sunglasses) to prevent him/her from

viewing events on the monitor. An experimenter controlled the study from an area located
out of view of the infant, either in the same or a different room. Infants' eye gaze data were
collected automatically via a corneal reflection eye-tracker, or on a digital videotape for later
offline coding.

Each infant saw a series of 6 test videos. Infants were assigned to one of four possible
trial orders that counterbalanced the direction of the actor's gaze (either LRRLRL or
RLLRLR, where L denotes gaze to the toy on the left and R denotes fixation to the toy on
the right), as well as which particular toy was located on the actor's left and right. Due to a
programming error, one lab presented the same trials in a randomized order instead. Videos
were separated by an unrelated attention-grabbing cartoon, which was played between trials
until the infant had looked towards it for approximately 1–2 seconds. The experiment lasted
approximately 1.5 minutes.

Exclusion Criteria

All data collected for the study (i.e., every infant for whom a data file was generated,
regardless of how many trials were completed) were given to the analysis team for
confirmatory analyses. Participants were only included in the analysis if they met all of the
criteria below. All exclusion rules are applied sequentially, and percentages reflect this
sequential application. N.B.: the first three criteria preemptively prevent participation
(except in case of erroneously running the experiment with children outside of the inclusion
guidelines).

<div align="center">**Analysis overview**</div>

Data exclusion

Labs were asked to submit all data collected as part of the study to the analysis team. Data were first screened to determine whether labs contributed useable data and whether infants met our inclusion criteria. Note that some infants had more than one reason for exclusion, and exclusion criteria were applied sequentially.

- *Lab reliability.* Data from two of the labs using the hand-coding method were excluded after extensive discussions with the participating laboratories. One lab could not achieve an acceptable level of inter-rater reliability, due to difficulty coding infant eye movements from the available videos. A second lab initially coded the data incorrectly (i.e., coded gaze shift from face to object differently than had been specified), but then had insufficient resources to re-code the data. There were 104 (14.50%) infants who were tested in these labs.

- *Age.* There were 55 (9%) infants who were tested but were out of our target age groups (6-9 months and 12-15 months).

- *Language background.* There were 50 (9%) infants who were tested but did not meet our inclusion criteria for either the monolingual or bilingual group. For example, an infant who heard English 20% of the time and Italian 80% of the time would not meet the criteria as either monolingual (at least 90% exposure to one language) or bilingual (at least 25% exposure to each of two languages).

- *Full-term.* We defined full-term as gestation times greater than or equal to 37 weeks. There were 10 (2%) infants who were tested but did not meet this criterion.

- *No diagnosed developmental disorders.* We excluded data from 1 (0.20%) infant with a

470   parent-reported developmental disorder.

471   • *Session errors.* There were 25 (5.07%) infants excluded from the analysis due to issues

472   including: 12 for equipment failure, 10 for fussiness, and 3 for parental/external

473   interference.

474   • *Insufficient face-to-object saccades.* Following Senju and Csibra (2008), and per our

475   pre-registration, we also excluded any infant who did not make at least one gaze shift

476   from face to object during the window of analysis in at least three of the six trials. A

477   further 145 (31.05%) infants were excluded from analyses for this reason.

478   • *Failure to attend.* We also excluded any trials in which infants did not look at the

479   congruent or incongruent object during the window of analysis. This meant that each

480   infant contributed a different number of trials. An additional 360 trials (23.03%) were

481   excluded from the analyses. This left us with a total number of 1563 valid trials

482   (81.28% of the data after the previous screenings) for later analyses: 211 trials for

483   6-to-9-month-old monolinguals (73.52% of the data), 714 trials for 12-to-15-month-old

484   monolinguals (83.80% of the data), 201 trials for 6-to-9-month-old bilinguals (74.44%

485   of the data), and 437 trials for 12-to-15-month-old bilinguals (85.02% of the data).

486   One lab mistakenly used a preliminary rather than the final version of the experiment.

487   The version used contained the same experimental stimuli and events as the final version

488   with two exceptions: the attention getter to recruit the infant's attention to the screen

489   differed and the aspect ratio of the on-screen stimuli differed slightly. As this version of the

490   experiment was only very slightly different from the final version, these data were retained

491   for analysis.

Areas of interest and data pre-processing.

On eye-tracking setups, following Senju & Csibra (2008), we established three areas of interest (AOIs) on each trial (see Figure 1): the actor's entire face (taking into account the model's head movements) and two areas surrounding each of the two objects (corresponding to the size of the largest object). These rather generous AOIs maximized consistency between eye-tracking coding and human coding. The two object AOIs were labeled as congruent (i.e., the object target of the actor's gaze) and incongruent (i.e., the object that was not the target of the actor's gaze). Pixel coordinates for the AOIs were amended proportionally to each individual lab's screen resolution.

Eye-trackers measured the coordinates of eye gaze, from which the direction and duration of fixations and gaze shifts were calculated. See supplemental materials for details of hardware used in each lab. Most eye-tracking software comes with built-in algorithms to parse fixations and gaze shifts, but these are optimized for adult data and perform suboptimally in noisy infant data (Hessels, Andersson, Hooge, Nyström, & Kemner, 2015; van Renswoude et al., 2018; Wass, Smith, & Johnson, 2013). To overcome this, and to standardize results between labs using different eye-tracking systems, we implemented a common approach using the GazePath tool for fixation and saccade detection, as outlined in van Renswoude et al. (2018). This approach is optimized for dealing with noisy infant data and individual differences that are expected between infants of different ages.

For labs that did not have an eye-tracker, trained human coders examined videos of infants' faces frame-by-frame to identify fixations and gaze shifts. Fixations were coded for duration and location with respect to the areas of interest (i.e., congruent object, incongruent object, actor, or off-target). Shifts were coded for direction, defined with respect to the horizontal and vertical midlines; i.e., movement could be left, right, down, and/or up. For these labs, a target minimum of 25% of participants were double-coded by a second human

517 coder and reliability estimates computed. Ultimately 27% of participants were double-coded.
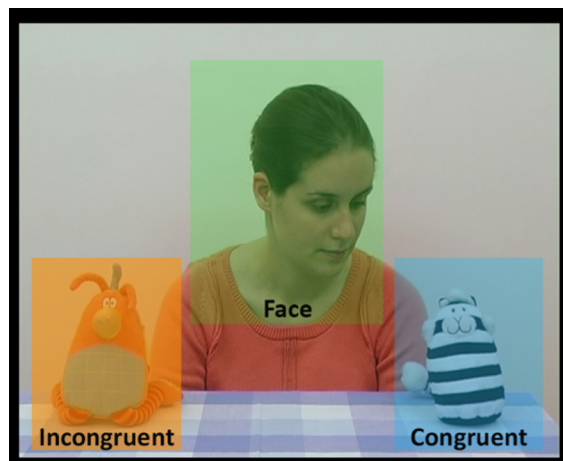
Figure 1. Screenshot of one of the videos presented to infants showing the three areas of interest (AOIs) used: face, congruent object, and incongruent object.

518 **Data reliability**

519 Because of the variability across labs in terms of methods and setups, different intrinsic
520 reliability issues emerged regarding data consistency across different eye-tracker setups,
521 between different human coders, and between eye-tracker and manual coding setups. These
522 issues have been addressed in three different ways. First, as described above, all eye-tracking
523 data were processed using the same GazePath tool, which is optimized to account for
524 variability across different ages, populations, and setups (van Renswoude et al., 2018).
525 Second, all labs using human coding rather than an eye-tracker double coded a minimum of
526 25% of their data. For 6- to 9-month-olds, frame and shift agreement ranged from
527 98.27-99.27% and 95.40-99.55%, respectively. For 12- to 15-month-olds, frame and shift
528 agreement ranged from 96.01-99.30% and 90.54-99.63%, respectively. These numbers do not
529 include the one laboratory described above whose data were excluded due to low inter-rater
530 reliability, which obtained well below 70% agreement due to poor video quality. One lab had
531 additionally planned to hand-code eye-tracking data to assess the comparability of

532   eye-tracking and human-coded data, but was unable to successfully do so due to unforeseen

533   technical and staffing issues. Overall, offline and eye-tracking-coded data each appeared to

534   have good reliability, although we were not able to assess the comparability of these

535   approaches.

Results

Dependent variables

538   Following previous studies using this paradigm (Senju & Csibra, 2008; Szufnarowska et

539   al., 2014), we investigated infants' gaze-following abilities via several different approaches.

540   Each approach focused on infants' looking behaviors to the areas of interest starting from

541   the point in time when the model started to turn her head (4 seconds – 100 frames – from

542   the beginning of the trial) to the end of the trial (10 seconds – 250 frames – from the

543   beginning of the trial). We measured four different dependent variables for each infant on

544   each trial. Three measures have been used in previous studies: first look, frequency of looks,

545   and duration of looks (Senju & Csibra, 2008; Szufnarowska et al., 2014). We included an

546   additional measure, latency, as we reasoned that infants' reaction time to follow an actor's

547   gaze might show interesting development over the first two years of life, and might be a

548   potentially sensitive measure. Exploring these four variables in the context of our large

549   sample size can provide insight for future studies about the expected effect sizes for different

550   analytic approaches.

551   **First look.**   This measured whether the infant shifted their gaze from the face AOI

552   to one of the object AOIs. This yielded a binary variable indicating whether the infant

553   showed a congruent gaze shift towards the actor's target (coded as 1), an incongruent gaze

554   shift towards the other object (coded as 0), or no shift (coded as missing).

555   **Frequency of looks.**   This yielded two values for each infant: the number of times

556 the infant shifted their gaze from the face AOI to the congruent AOI, and the number of

557 times the infant shifted their gaze from the face AOI to the incongruent AOI.

558   **Duration of looks.**   This measured the total duration of fixation to the congruent

559 AOI and to the incongruent AOI. Thus, each infant had two values. These values were

560 log-transformed prior to analysis in order to correct for the skew typical of looking time data

561 (Csibra, Hernik, Mascaro, Tatone, & Lengyel, 2016).

562   **Latency.**   This established infants' reaction times to follow the actor's gaze in

563 milliseconds. On each trial, latency was coded as the latency of the first face-to-object gaze

564 shift, irrespective of whether the first look was to the congruent or incongruent AOIs. As

565 raw latency scores were non-normal, the scores were log-transformed prior to analysis,

566 following the pre-registered analysis plan.

567 **Analysis approach**

568   All planned analyses were pre-registered at osf.io/2ey3k/. Following previous

569 large-scale multi-lab studies with infants (e.g., ManyBabies Consortium, 2020;

570 Byers-Heinlein, Tsui, et al., 2020), we used two complementary data analysis frameworks:

571 meta-analysis and mixed-effects regression. Under the meta-analytic framework, we

572 conducted standard analyses within each lab and then combined these results across labs.

573 An advantage of this approach is that it is easy to understand, and is comparable to results

574 from meta-analyses that gather data from published studies. Under the mixed-effects

575 regression framework, we modeled raw trial-by-trial data from each infant. Because this

576 approach models raw data directly, it can have greater statistical power to detect effects.

577 **Confirmatory Analyses**

578 **Meta-analytic framework.** Under this framework, we first calculated mean scores

579 for each individual infant on the four dependent variables. For first look, frequency of looks,

580 and total duration of looks, we calculated proportion difference scores for each infant, which

581 subtracted the mean value for incongruent trials (i) from the mean for congruent trials (c),

582 and divided by the total number of trials that contributed to that measure [(c - i)/(c + i)].

583 Trials without values for a particular measure were excluded from the calculation. For

584 latency, we limited the analysis to only those trials with a congruent first look, and for the

585 meta-analytic model, we focused on the mean latency for each infant to look towards the

586 congruent AOI. We then collapsed these for each dataset (i.e., a combination of lab,

587 bilingualism status, and age group) to calculate a grand mean (M) and standard deviation

588 (sd) across participants in each dataset. Finally, using the formula $dz = M/sd$, the derived M

589 and sd were used to compute a within-subject Cohen's d for first look, frequency of looks,

590 and total duration of looks. For latency, we deviated from the pre-registered analysis plan.

591 As the analysis was limited to latency towards the congruent AOI, it was not ideal to

592 generate a Cohen's d effect size without a comparison between two means. Instead of

593 computing a within-subject Cohen's d, the raw grand mean (M) and standard deviation (sd)

594 in milliseconds across participants were entered into the meta-analytic model for latency.

595 Sampling variance for each mean was calculated based on the formula sd^2/n.

596 Random-effects meta-analysis models with a restricted maximum-likelihood estimator

597 (REML) were fit with the metafor package (Viechtbauer, 2010). A logistic model was fit for

598 first look, frequency of looks, and total duration of looks as each infant's score was bounded

599 between 0 and 1. A linear model was fit for latency. To account for the dependence between

600 mono- and bilingual datasets stemming from the same lab, we included laboratory as a

601 random factor. Bilingualism (0 = monolingual, 1 = bilingual), and age group (0 = 6–9

602 months, 1 = 12–15 months) were dummy coded.

603 Our main meta-analytic model for each dependent variable was:

604   dz ~ 1 + bilingual + age + bilingual * age

```r
## Datasets for First Look analysis
#The proportion of first-shifts to congruent versus invcongruent trials by infant
d_first <- d %>%
  filter(!is.na(first_shift)) %>% # Select only trials that had a shift
  select(-latency, -n_shift_congruent, -n_shift_incongruent, -fixation_congruent, - fixa

d_first_meta <- d_first %>%
  group_by_at(vars(-trial_num)) %>%
  summarise(n = n()) %>%
  spread(key = first_shift, value = n, fill = 0) %>%
  mutate(prop = (congruent-incongruent)/(congruent+incongruent)) %>% # Calculate propor
  select(-congruent, -incongruent) %>%
  filter(!is.na(prop)) %>%
  group_by(subid, age_group, lang_group, lab) %>%
  summarise(prop = mean(prop, na.rm = TRUE))

##Meta-analysis
d_z_first <- d_first_meta %>%
  group_by(subid, lab, age_group, lang_group) %>%
  summarise(mean_prop = mean(prop, na.rm = TRUE)) %>%
  group_by(lab, age_group, lang_group) %>%
  summarise(d = mean(mean_prop, na.rm = TRUE) / sd(mean_prop, na.rm = TRUE),
            n = length(unique(subid)),
            d_var = d_var_calc(n, d))

first_meta <- metafor::rma(d ~ lang_group * age_group, vi = d_var,
```

```
                    slab = lab, data = d_z_first, method = "REML")
```

⁶⁰⁵ **First look.**   We began by examining the relation of the proportion of congruent first

⁶⁰⁶ looks to bilingualism and age, fitting the main effect model to the 32 separate group means

⁶⁰⁷ and variances (after aggregating by lab, age, and language group). Note that, because

⁶⁰⁸ incongruent trials are subtracted from congruent in the numerator of this calculation, the

⁶⁰⁹ first look proportion scores are centered around 0 with negative values indicating behaviors

⁶¹⁰ in the direction of incongruent trials, and positive values indicating greater proportion of

⁶¹¹ behaviors in the direction of congruent trials. The meta-analysis on first look yielded a mean

⁶¹² effect size estimate of 0.79 (CI = [0.28 - 1.29], $z = 3.07$, $p = .002$) for 6–9 month-old

⁶¹³ monolingual infants (the reference level). Age yielded an additional effect of 0.43 (CI = [-0.17

⁶¹⁴ - 1.03], $z = 1.39$, $p = .165$), suggesting a mean increase in the proportion of first looks to the

⁶¹⁵ target for 12–15 month-old monolingual infants, although this effect was not statistically

⁶¹⁶ significant. The bilingual coefficient of 0 (CI = [-0.72 - 0.72], $z = 0$, $p = .997$) suggests no

⁶¹⁷ difference between bilingual and monolingual infants at 6–9 months (the reference age).

⁶¹⁸ Moreover, the interaction between bilingualism and age was small and not statistically

⁶¹⁹ different from zero ($\beta = -0.02$, CI = [-0.91 - 0.88], $z = -0.04$, $p = .970$). Taken together, this

⁶²⁰ suggests no reliable difference in proportion of first looks to the target between bilingual and

⁶²¹ monolingual infants at either age. A forest plot for this meta-analysis is shown in Figure 2.

```
alpha <- .05


d_z_first_6to9 <- d_z_first%>%

  filter(age_group == "6-9 mo")


first_lang_only_matched_in6to9 <- metafor::rma(d ~ lang_group, vi = d_var,

                                slab = lab, data = d_z_first_6to9, method = "REML")
```

```r
d_z_first_12to15 <- d_z_first %>%

  filter(age_group == "12-15 mo")


first_lang_only_matched_in12to15 <- metafor::rma(d ~ lang_group, vi = d_var,

                                    slab = lab, data = d_z_first_12to15, method = "REML")


p_first_lang_6to9 <- predict(first_lang_only_matched_in6to9, newmods =  c(0,1)) %>%

  as_tibble %>%

  mutate(lang_group = levels(d_z_first_6to9$lang_group),

         age_group = "6-9 mo",

         lab = "Meta-analytic estimate")


p_first_lang_12to15 <- predict(first_lang_only_matched_in12to15, newmods =  c(0,1)) %>%

  as_tibble %>%

  mutate(lang_group = levels(d_z_first_12to15$lang_group),

         age_group = "12-15 mo",

         lab = "Meta-analytic estimate")


first_forest_data <- ungroup(d_z_first) %>%

  mutate(pred = d,

         ci.lb = d - qnorm(alpha / 2, lower.tail = FALSE) * sqrt(d_var),

         ci.ub = d + qnorm(alpha / 2, lower.tail = FALSE) * sqrt(d_var),

         inverse_vars = 1/d_var,

         age_group = as.character(age_group)) %>%

  bind_rows(p_first_lang_6to9) %>%

  bind_rows(p_first_lang_12to15) %>%

  mutate(age_group = fct_relevel(age_group, c("6-9 mo", "12-15 mo", "")),
```

```r
     lab = fct_relevel(lab, "Meta-analytic estimate"))


ggplot(first_forest_data,

      aes(x = lab, y = pred,

          ymin = ci.lb, ymax = ci.ub, col = lang_group)) +

  geom_point(aes(y = d, size = inverse_vars),

            position = position_dodge(width = .2)) +

  geom_point(data = filter(first_forest_data, lab == "Meta-analytic estimate"), pch = 5)

  geom_linerange(position = position_dodge(width = .2)) +

  facet_grid(age_group ~ ., scales = "free", space = "free") +

  geom_hline(yintercept = 0, linetype = "dashed", color = "grey") +

  coord_flip() +

  scale_size_continuous(guide = FALSE) +

  scale_colour_manual(name = "Language group", values = c("#bdbdbd", "#636363", "#000000

  scale_y_continuous(limits=c(-1, 4)) +

  xlab("Lab") +

  ylab("Effect Size: First look") +

  theme(legend.position = "bottom")
```

```r
## Datasets for frequency analysis
d_freq <- d %>%

  select(-first_shift, -latency, -fixation_congruent, - fixation_incongruent) %>%

  filter((n_shift_congruent + n_shift_incongruent) > 0) %>% # Select only trials that h

  gather(key = "object", value = "n_shift", n_shift_congruent, n_shift_incongruent) %>%

  mutate(object = case_when(

    object == "n_shift_congruent" ~ "congruent",

    object == "n_shift_incongruent" ~ "incongruent"
```
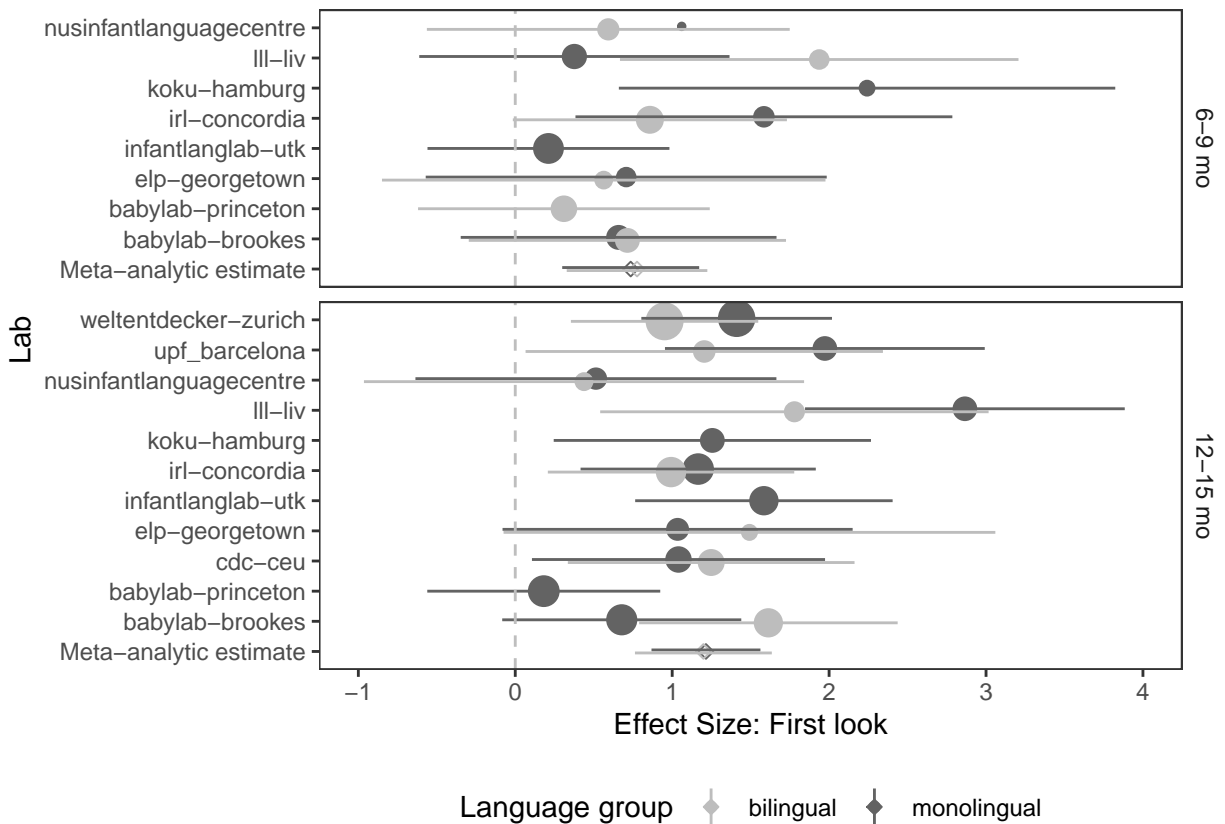
Figure 2. Forest plot for the cross-lab meta-analysis on the proportion of first look.

```
)) %>%

  mutate(object = as.factor(object))


d_freq_meta <- d  %>%

  group_by_at(vars(-trial_num)) %>%

  select(-first_shift, -latency, -fixation_congruent, - fixation_incongruent) %>%

  filter((n_shift_congruent + n_shift_incongruent) > 0) %>% # Select only trials that h

  mutate(prop = (n_shift_congruent -  n_shift_incongruent)/(n_shift_congruent + n_shift_

  group_by_at(vars(-trial_num, - prop)) %>%

  mutate(prop = mean(prop)) %>% # Average proportion difference score by baby

  group_by(subid, age_group, lang_group, lab) %>%

  summarise(prop = mean(prop, na.rm = TRUE))
```

```
##Meta-analysis

d_z_freq <- d_freq_meta %>%

  group_by(lab, age_group, lang_group) %>%

  summarise(d = mean(prop, na.rm = TRUE) / sd(prop, na.rm = TRUE),

            n = length(unique(subid)),

            d_var = d_var_calc(n, d))



freq_meta <- metafor::rma(d ~ lang_group * age_group, vi = d_var,

                          slab = lab, data = d_z_freq, method = "REML")
```

622   **Frequency of looks.**   We then investigated the relation of frequency of looks to

623   bilingualism and age group. The overall mean effect size estimate for 6–9 month-old

624   monolingual infants was 0.73 (CI = [0.22 - 1.23], $z = 2.83$, $p = .005$). Age yielded an

625   additional effect of 0.48 (CI = [-0.13 - 1.08], $z = 1.55$, $p = .121$), but was not statistically

626   significant. There was no evidence that bilingual infants differed from monolingual infants at

627   6–9 months, as the additional effect of bilingualism was 0 (CI = [-0.72 - 0.72], $z = 0$,

628   $p = .998$). Moreover, the interaction between bilingualism and age yielded a very small effect

629   of 0.10 (CI = [-0.80 - 0.99], $z = 0.22$, $p = .829$), implying no differences between monolingual

630   and bilingual infants in frequency of target looks at both ages. A forest plot for this

631   meta-analysis is shown in Figure 3.

```
alpha <- .05



d_z_freq_6to9 <- d_z_freq%>%

  filter(age_group == "6-9 mo")



freq_lang_only_matched_in6to9 <- metafor::rma(d ~ lang_group, vi = d_var,
```

```r
                                        slab = lab, data = d_z_freq_6to9, method = "REML")


d_z_freq_12to15 <- d_z_freq%>%

  filter(age_group == "12-15 mo")


freq_lang_only_matched_in12to15 <- metafor::rma(d ~ lang_group, vi = d_var,

                                      slab = lab, data = d_z_freq_12to15, method = "REML")


p_freq_lang_6to9 <- predict(freq_lang_only_matched_in6to9, newmods =  c(0,1)) %>%

  as_tibble %>%

  mutate(lang_group = levels(d_z_freq_6to9$lang_group),

         age_group = "6-9 mo",

         lab = "Meta-analytic estimate")


p_freq_lang_12to15 <- predict(freq_lang_only_matched_in12to15, newmods =  c(0,1)) %>%

  as_tibble %>%

  mutate(lang_group = levels(d_z_freq_12to15$lang_group),

         age_group = "12-15 mo",

         lab = "Meta-analytic estimate")


freq_forest_data <- ungroup(d_z_freq) %>%

  mutate(pred = d,

         ci.lb = d - qnorm(alpha / 2, lower.tail = FALSE) * sqrt(d_var),

         ci.ub = d + qnorm(alpha / 2, lower.tail = FALSE) * sqrt(d_var),

         inverse_vars = 1/d_var,

         age_group = as.character(age_group)) %>%

  bind_rows(p_freq_lang_6to9)%>%
```

```r
  bind_rows(p_freq_lang_12to15)%>%

  mutate(age_group = fct_relevel(age_group, c("6-9 mo", "12-15 mo", "")),
         lab = fct_relevel(lab, "Meta-analytic estimate"))


ggplot(freq_forest_data,
       aes(x = lab, y = pred,
           ymin = ci.lb, ymax = ci.ub, col = lang_group)) +
  geom_point(aes(y = d, size = inverse_vars),
             position = position_dodge(width = .2)) +
  geom_point(data = filter(freq_forest_data, lab == "Meta-analytic estimate"), pch = 5)
  geom_linerange(position = position_dodge(width = .2)) +
  facet_grid(age_group ~ ., scales = "free", space = "free") +
  geom_hline(yintercept = 0, linetype = "dashed", color = "grey") +
  coord_flip() +
  scale_size_continuous(guide = FALSE) +
  scale_colour_manual(name = "Language group", values = c("#bdbdbd", "#636363", "#000000
  scale_y_continuous(limits=c(-1, 4)) +
  xlab("Lab") +
  ylab("Effect Size: Frequency of looks") +
  theme(legend.position = "bottom")
```

```r
## Datasets for duration analysis
d_duration <- d %>%
  select(-first_shift, -latency, -n_shift_congruent, -n_shift_incongruent) %>%
  filter(fixation_congruent + fixation_incongruent > 0) %>% # Select only trials that h
  gather(key = "object", value = "duration", fixation_congruent, fixation_incongruent)
  mutate(object = case_when(
```
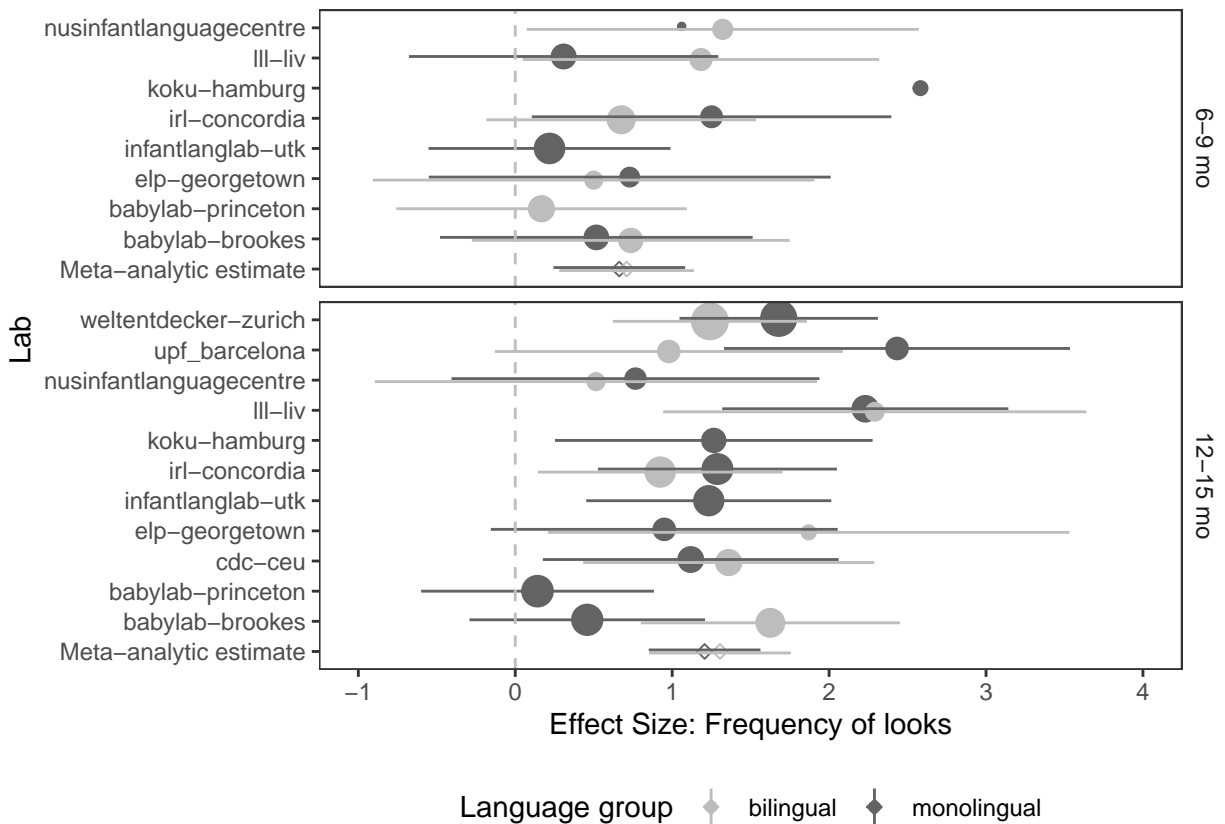
Figure 3. Forest plot for the cross-lab meta-analysis on frequency of looks.

```
    object == "fixation_congruent" ~ "congruent",

    object == "fixation_incongruent" ~ "incongruent"

)) %>%

mutate(object = as.factor(object)) %>%

mutate(duration = log(duration + 1)) # Log-transform duration scores, adding one to


d_duration_meta <- d %>%

  select(-first_shift, -latency, -n_shift_congruent, -n_shift_incongruent) %>%

  filter(fixation_congruent + fixation_incongruent > 0) %>%

  mutate(prop = (fixation_congruent - fixation_incongruent)/(fixation_congruent + fixati

  group_by_at(vars(-trial_num, - prop)) %>%

  mutate(prop = mean(prop)) # Average proportion difference score by baby
```

```
##Meta-analysis

d_z_dur <- d_duration_meta %>%

  group_by(lab, age_group, lang_group) %>%

  summarise(d = mean(prop, na.rm = TRUE) / sd(prop, na.rm = TRUE),

            n = length(unique(subid)),

            d_var = d_var_calc(n, d))



library(metafor)



dur_meta <- rma(d ~ lang_group * age_group, vi = d_var,

                slab = lab, data = d_z_dur, method = "REML")
```

632   **Duration of looks.** The cross-lab meta-analysis on duration of looks yielded a

633 non-significant mean effect size estimate for 6–9 month-old monolingual infants of 0.32 (CI =

634 [-0.09 - 0.72], $z = 1.53$, $p = .125$). Age yielded a non-significant additional effect of 0.08 (CI

635 = [-0.39 - 0.54], $z = 0.32$, $p = .752$). The additional bilingualism effect of -0.06 (CI = [-0.64 -

636 0.52], $z = -0.21$, $p = .837$) was also not statistically significant, suggesting that 6–9

637 month-old bilingual infants did not look significantly longer to the target relative to the

638 distractor compared to monolingual infants. Moreover, the interaction between bilingualism

639 and age yielded a very small effect of 0.08 (CI = [-0.62 - 0.77], $z = 0.22$, $p = .824$),

640 suggesting no evidence of differences between monolingual and bilingual infants across both

641 ages. A forest plot for this meta-analysis is shown in Figure 4.

```
alpha <- .05



d_z_dur_6to9 <- d_z_dur %>%

  filter(age_group == "6-9 mo")
```

```r
dur_lang_only_matched_in6to9 <- metafor::rma(d ~ lang_group, vi = d_var,
                                slab = lab, data = d_z_dur_6to9, method = "REML")


d_z_dur_12to15 <- d_z_dur%>%
  filter(age_group == "12-15 mo")


dur_lang_only_matched_in12to15 <- metafor::rma(d ~ lang_group, vi = d_var,
                                slab = lab, data = d_z_dur_12to15, method = "REML")


p_dur_lang_6to9 <- predict(dur_lang_only_matched_in6to9, newmods =  c(0,1)) %>%
  as_tibble %>%
  mutate(lang_group = levels(d_z_dur_6to9$lang_group),
        age_group = "6-9 mo",
        lab = "Meta-analytic estimate")


p_dur_lang_12to15 <- predict(dur_lang_only_matched_in12to15, newmods =  c(0,1)) %>%
  as_tibble %>%
  mutate(lang_group = levels(d_z_dur_12to15$lang_group),
        age_group = "12-15 mo",
        lab = "Meta-analytic estimate")


dur_forest_data <- ungroup(d_z_dur) %>%
  mutate(pred = d,
        ci.lb = d - qnorm(alpha / 2, lower.tail = FALSE) * sqrt(d_var),
        ci.ub = d + qnorm(alpha / 2, lower.tail = FALSE) * sqrt(d_var),
        inverse_vars = 1/d_var,
```

```r
        age_group = as.character(age_group)) %>%
  bind_rows(p_dur_lang_6to9)%>%
  bind_rows(p_dur_lang_12to15)%>%
  mutate(age_group = fct_relevel(age_group, c("6-9 mo", "12-15 mo", "")),
         lab = fct_relevel(lab, "Meta-analytic estimate"))


ggplot(dur_forest_data,
       aes(x = lab, y = pred,
           ymin = ci.lb, ymax = ci.ub, col = lang_group)) +
  geom_point(aes(y = d, size = inverse_vars),
             position = position_dodge(width = .2)) +
  geom_point(data = filter(dur_forest_data, lab == "Meta-analytic estimate"), pch = 5)+
  geom_linerange(position = position_dodge(width = .2)) +
  facet_grid(age_group ~ ., scales = "free", space = "free") +
  geom_hline(yintercept = 0, linetype = "dashed", color = "grey") +
  coord_flip() +
  scale_size_continuous(guide = FALSE) +
  scale_colour_manual(name = "Language group", values = c("#bdbdbd", "#636363", "#000000
  scale_y_continuous(limits=c(-1, 4)) +
  xlab("Lab") +
  ylab("Effect Size: Duration of looks") +
  theme(legend.position = "bottom")

## Datasets for latency analysis
d_latency <- d %>%
  select(-n_shift_congruent, -n_shift_incongruent, -fixation_congruent, - fixation_incon
  rename("object" = "first_shift") %>%
```
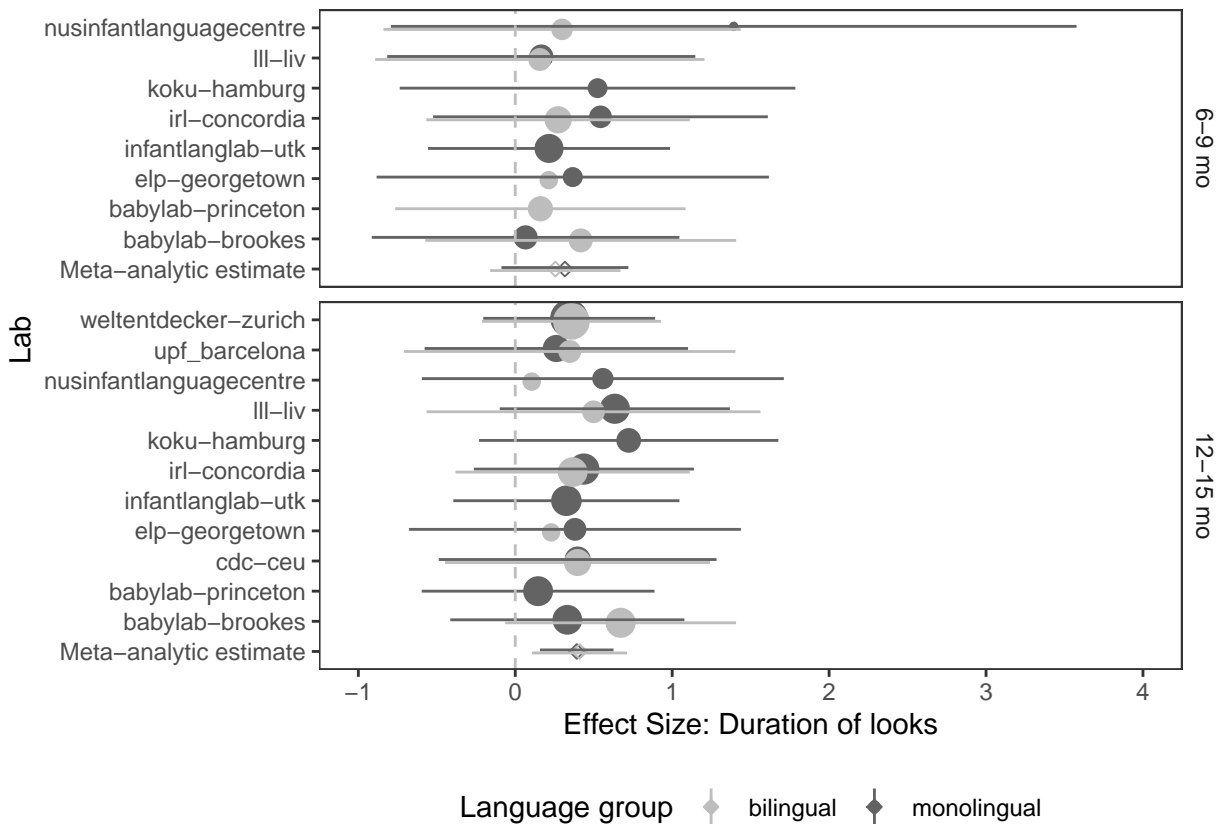
Figure 4. Forest plot for the cross-lab meta-analysis on duration of looks.

```r
  filter(!is.na(object)) %>% # only trials with first shifts

  mutate(latency = log(latency + 1)) # Log transform latency scores, adding one to deal


d_latency_meta <- d %>%

  select(-n_shift_congruent, -n_shift_incongruent, -fixation_congruent, - fixation_incon

  rename("object" = "first_shift") %>%

  filter(!is.na(object)) %>%

  mutate(object = as.factor(object)) %>%

  group_by_at(vars(-trial_num, - latency)) %>%

  mutate(latency = mean(latency)) # Average proportion difference score by baby


##Meta-analysis
```

```r
d_z_latency <- d_latency_meta %>%

  filter(object != "incongruent")%>%

  group_by(lab, age_group, lang_group, subid) %>%

  summarise(latency = mean(latency))%>%

  group_by(lab, age_group, lang_group) %>%

  summarise(mean = mean(latency),

            sd = sd(latency),

            n = length(unique(subid)),

            var = ((sd^2)/n)) #sampling variance


Latency_meta <- metafor::rma(mean ~ lang_group * age_group, vi = var,

                    slab = lab, data = d_z_latency, method = "REML")


Latency_meta_interaction <- metafor::rma(mean ~ age_group:lang_group -1, vi = var,

                    slab = lab, data = d_z_latency, method = "REML") #alternative param

pairwise <- anova(Latency_meta_interaction, L=rbind(c(1,0,-1,0),c(0,1,0,-1))) #pairwise
```

Latency.   The cross-lab meta-analysis on latency towards the congruent object

yielded a reference-level mean latency estimate of 2,345.76 milliseconds (CI = [2,056.47 -

2,635.06], $z = 15.89$, $p =< .001$) for 6–9 month-old monolingual infants. With the effect of

age, the mean latency estimate decreased significantly, with an estimated difference for the

older group of -493.06 milliseconds (CI = [-835.03 - -151.09], $z = -2.83$, $p = .005$); in other

words, 12–15 month-old monolingual infants were faster than 6–9 month-old monolingual

infants to fixate the congruent object. Bilingualism increased the mean latency estimate by

378.29 milliseconds (CI = [-26.76 - 783.34], $z = 1.83$, $p = .067$); in other words, the estimate

for bilinguals suggested they might be slower than monolingual infants to fixate the

651 congruent object, but this was non-significant. The interaction between bilingualism and age

652 suggested a possible attenuation of this pattern for older 12–15 month-old bilingual versus

653 monolingual infants, although again this did not reach statistical significance (estimate =

654 -437.30, CI = [-930.57 - 55.97], $z = -1.74$, $p = .082$). Pairwise comparisons revealed that, at

655 the age of 12–15 months, there was no longer any evidence of a difference in target fixation

656 latency between monolingual and bilingual infants (estimate $= 59.01$, $se = 143.63$, $z = 0.41$,

657 $p = .681$). A forest plot for this meta-analysis is shown in Figure 5.

```r
alpha <- .05


d_z_latency_6to9 <- d_z_latency%>%

  filter(age_group == "6-9 mo")


latency_lang_only_matched_in6to9 <- metafor::rma(mean ~ lang_group, vi = var,

                                    slab = lab, data = d_z_latency_6to9, method = "REML")


d_z_latency_12to15 <- d_z_latency%>%

  filter(age_group == "12-15 mo")


latency_lang_only_matched_in12to15 <- metafor::rma(mean ~ lang_group, vi = var,

                                    slab = lab, data = d_z_latency_12to15, method = "REML"

p_latency_lang_6to9 <- predict(latency_lang_only_matched_in6to9, newmods =  c(0,1)) %>%

  as_tibble %>%

  mutate(lang_group = levels(d_z_latency_6to9$lang_group),

         age_group = "6-9 mo",

         lab = "Meta-analytic estimate")
```

```r
p_latency_lang_12to15 <- predict(latency_lang_only_matched_in12to15, newmods = c(0,1))

  as_tibble %>%

  mutate(lang_group = levels(d_z_latency_12to15$lang_group),

         age_group = "12-15 mo",

         lab = "Meta-analytic estimate")


latency_forest_data <- ungroup(d_z_latency) %>%

  mutate(pred = mean,

         ci.lb = mean - qnorm(alpha / 2, lower.tail = FALSE) * sqrt(var),

         ci.ub = mean + qnorm(alpha / 2, lower.tail = FALSE) * sqrt(var),

         inverse_vars = 1/var,

         age_group = as.character(age_group)) %>%

  bind_rows(p_latency_lang_6to9)%>%

  bind_rows(p_latency_lang_12to15)%>%

  mutate(age_group = fct_relevel(age_group, c("6-9 mo", "12-15 mo", "")),

         lab = fct_relevel(lab, "Meta-analytic estimate"))


ggplot(latency_forest_data,

       aes(x = lab, y = pred,

           ymin = ci.lb, ymax = ci.ub, col = lang_group)) +

  geom_point(aes(y = mean, size = inverse_vars),

             position = position_dodge(width = .2)) +

  geom_point(data = filter(latency_forest_data, lab == "Meta-analytic estimate"), pch =

  geom_linerange(position = position_dodge(width = .2)) +

  facet_grid(age_group ~ ., scales = "free", space = "free") +

  geom_hline(yintercept = 0, linetype = "dashed", color = "grey") +

  coord_flip() +
```

```
scale_size_continuous(guide = FALSE) +

scale_colour_manual(name = "Language group", values = c("#bdbdbd", "#636363", "#000000

xlab("Lab") +

ylab("Mean Latency to Congruent AOI (ms)") +

theme(legend.position = "bottom")
```
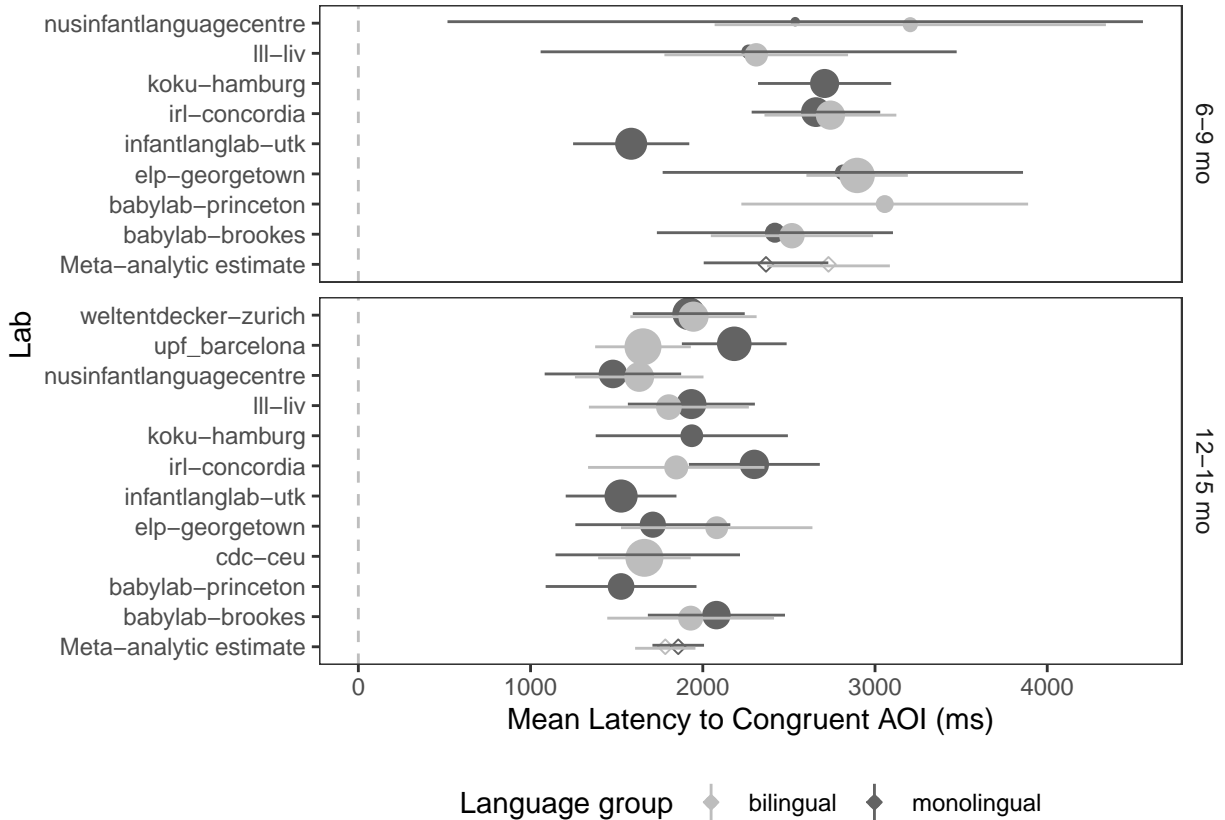

Figure 5. Forest plot for the cross-lab meta-analysis on latency.

Summary of meta-analysis. Overall, our meta-analytic models revealed that infants followed the actor's gaze to the congruent object, as measured by their first looks and frequency of looks. Duration of look, on the other hand, was not significantly impacted by the actor's gaze or either of our moderating factors (age and bilingualism). The first look and frequency of looks models revealed medium effects for age, although age was not statistically significant in either model. The direction of these effects would suggest that 12–15 month old infants are better at gaze-following than 6–9 month old infants. This pattern was repeated in

our meta-analytic model of latency, which revealed that older infants were significantly faster than younger infants to fixate the congruent object after the actor's gaze shift. Latency of fixation, moreover, was the only measure where we found any suggestion of a difference between bilingual and monolingual infants. Though it did not reach the significance threshold of $p < .05$, the coefficient direction and magnitude of the latency model showed that younger bilinguals were slower to fixate on the target object than their monolingual peers. This possible effect was not observed for older infants, where by 12–15 months there was no evidence for different latencies between bilinguals and monolinguals. Together, all these results imply that older infants show more reliable gaze following than younger infants.

Mixed-effects regression framework

As opposed to the meta-analytic framework, the mixed-effects regression framework allowed us to model trial-level data from individual infants rather than analyzing averages. Mixed-effects models are described as such because they include both fixed effects and random effects. Our fixed effects modeled the main variables of interest: age, bilingualism, and aoi. Our random effects accounted for correlations in the data that could arise due to dependency between data from the same infants, lab, and test items. For each model, we planned to initially fit a maximal random effects structure (Barr, Levy, Scheepers, & Tily, 2013), while anticipating the need for pruning. We aimed to identify a pruned random-effects structure that would be well-supported by our data while conserving the most theoretically important effects (Matuschek, Kliegl, Vasishth, Baayen, & Bates, 2017). The approach to pruning random effects was somewhat exploratory, as we did not have a specific hypothesis about the random effects. Note that while the particular random effects structure of the model can affect the estimates of standard errors, in a balanced design it does not affect the estimates of the fixed effects, which were our main interest.

We modeled trial-level data for each infant, for the following dependent variables (DV):

- *first_shift*: A binary variable denoting the AOI of the first shift, where 0 is the incongruent object and 1 is the congruent object.

- *latency*: The time interval in milliseconds between the onset of the actor's head-turn, and the moment of first fixation on an object AOI.

- *freq_shift*: The number of times in the trial an infant shifted gaze towards the AOI.

- *total_look*: The total duration of fixations towards the AOI during the trial.

Our predictor variables were:

- *bilingual*: A dummy-coded variable where 0 is monolingual, 1 is bilingual.

- *age_days*: The infant's age in days, scaled and centred for ease of interpretation.

- *aoi*: A dummy-coded variable for analysis of freq_shift, total_look, and latency, for which data from both AOIs are reported. Here, 0 denotes the congruent AOI, and 1 denotes the incongruent AOI.

We ran separate models for each DV. We fit all models using the `lme4` package (Bates, Mächler, Bolker, & Walker, 2015). For first_shift, we fit a logistic model as this variable is binary at the trial level. The initial model specification was:

first_shift ~ bilingual * age_days + (1|subid) + (bilingual * age_days|lab) + (bilingual * age_days|item)

For latency, freq_shift, and total_look, we used a similar model with two modifications. First, we fit a linear model rather than a logistic model as these variables are continuous and unbounded. Second, we included an interaction with aoi in the fixed effects, and estimated corresponding random slopes where appropriate. This was necessary in order to estimate separate parameters for the congruent and incongruent AOIs (i.e., to model

712 whether latency to first fixation varies as a function of whether it is to the congruent or

713 incongruent AOI; whether infants shift more frequently to the congruent than the

714 incongruent AOI; and whether infants fixate more on the congruent than incongruent AOI).

715 For these three DVs, the initial model specification was:

716   DV ~ bilingual * age_days * aoi + (aoi|subid) + (bilingual * age_days * aoi|lab) +

717 (bilingual * age_days * aoi |item)

718   **First shift towards the AOI.**   Our final logistic model specification for first shift

719 was:

720   first_shift ~ bilingual * age_days + (1|subid) + (1|lab)

```r
first_glmer <- d_first %>%
  mutate(age_days = scale(age_days, scale = TRUE)) %>%
  filter(!is.na(first_shift)) %>%
  mutate(first_shift = fct_rev(first_shift)) %>% # So higher numbers mean more looks to
  glmer(first_shift ~ lang_group * age_days + (1|subid) + (1|lab),
  data = .,
  family = binomial
)


firstshift_coefs <- summary(first_glmer)$coef %>%
  as.data.frame %>%
  mutate_at(c("Estimate","Std. Error", "z value", "Pr(>|z|)"),
            function (x) signif(x, digits = 3)) %>%
  rename(SE = `Std. Error`,
         z = `z value`,
         p = `Pr(>|z|)`) %>%
```

Table 2

Coefficient estimates from a logistic mixed-effects model predicting the probability of making first looks to congruent objects.

	Estimate	SE	z	p
Intercept	0.971	0.105	9.270	<.001
bilingual	-0.010	0.126	-0.078	0.938
age_days	0.197	0.079	2.500	<.05
bilingual * age_days	-0.096	0.123	-0.779	0.436

```
  mutate_if(is.numeric, round, digits = 3) %>%

 mutate(p = case_when(

   p < .001 ~ "<.001",

   p < .01 ~ "<.01",

   p < .05 ~ "<.05",

   TRUE ~ as.character(p)))


rownames(firstshift_coefs) <- c("Intercept", "bilingual", "age_days",

                 "bilingual * age_days")


papaja::apa_table(firstshift_coefs, format.args = list(digits = 3),

               caption = "Coefficient estimates from a logistic mixed-effects model p

               col.names =c("","Estimate","$SE$","$z$","$p$"),

               align=c("l","l","c","c","c"))
```

721 Table 2 shows coefficient estimates from this model and Figure 6 visualizes this model.

722 Positive coefficients indicate a higher probability of making a first look to the congruent

723 object. The significant intercept indicated that infants were more likely to first look to the

724 congruent versus the incongruent object; moreover, a significant positive coefficient for age

725 indicated that older infants did so at an even higher rate. There was no obvious evidence for

726 a difference between monolingual and bilingual infants, and the interaction of bilingualism

727 and age was also not significant. Monolingual and bilingual infants, therefore, did not differ

728 in their probabilities of first looking to the congruent object across ages.

```r
d_first%>%
  mutate(pred_prob = predict(first_glmer, type ="response"))%>%
  mutate(first_shift = case_when(first_shift == "congruent" ~ 1, first_shift == "incong
  mutate(first_shift = as.integer(first_shift))%>%
  ggplot() +
  aes(x=age_days, y=pred_prob, color=lang_group) +
  geom_point(alpha = 1.00, aes(shape=lang_group), size=3.5) +
  geom_smooth(method="glm",
              aes(x=age_days, y=pred_prob),
              method.args = list(family = "quasibinomial"),
              se = FALSE)+
  ylab("Probability of first look to the congruent AOI") +
  xlab("Age in days") +
  geom_hline(yintercept=0.50, linetype="dashed", color = "#000000") +
  scale_y_continuous(limits=c(0.40, 1.00), breaks=seq(0.40,1.00,0.1)) +
  scale_colour_manual(name = "Language group", values = c("#bdbdbd", "#000000")) +
  scale_fill_manual(name = "Language group", values = c("#bdbdbd", "#000000")) +
  theme(text = element_text(size = 12), legend.position = "bottom") +
  labs(color  = "Language group", linetype = "Language group", shape = "Language group")
```
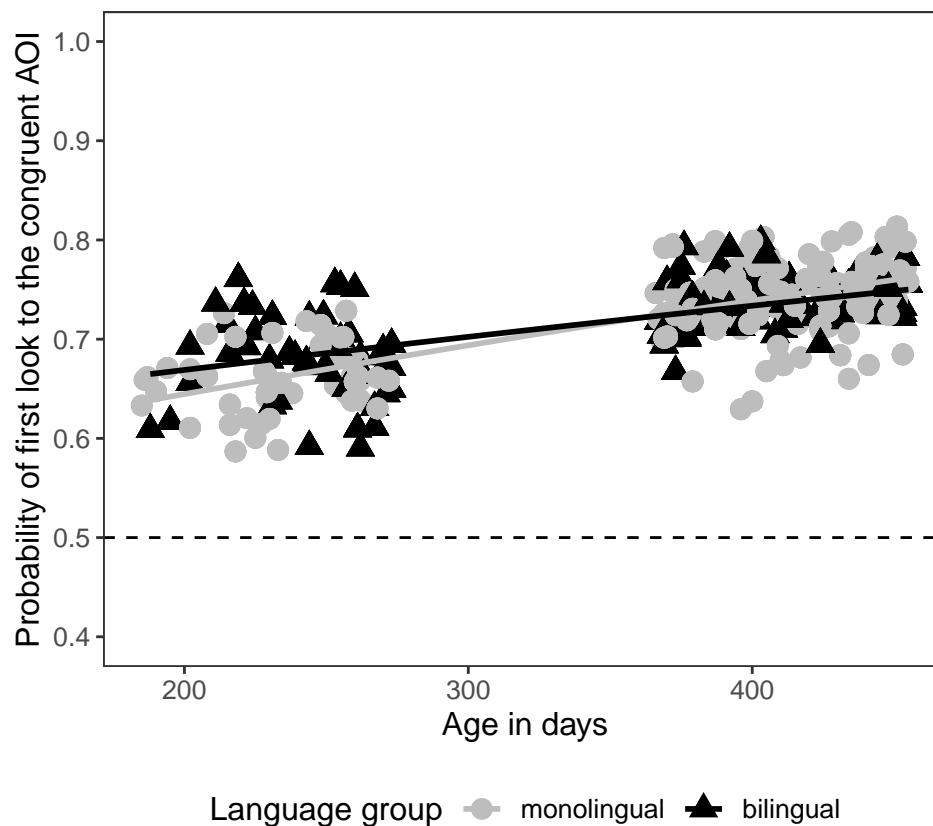
Figure 6. The logistic regression model predicting the probability of making first look to the congruent object, plotted with individual participants' probabilities.

⁷²⁹   **Frequency of shifting gaze towards the AOI.** The final model specification for

⁷³⁰ frequency of shift was:

⁷³¹   freq_shift ~ bilingual * age_days * aoi + (1|subid) + (1|item)

```r
freq_lmer <- d_freq %>%

  mutate(age_days = scale(age_days, scale = TRUE)) %>%

  lmer(n_shift ~ lang_group*age_days*object + (1|subid) + (1|trial_num),

  control = lmerControl("bobyqa"),

  data = .)


freq_coefs <- summary(freq_lmer)$coef %>%
```

```
  as.data.frame %>%

  select(-df)%>%

  mutate_at(c("Estimate","Std. Error", "t value", "Pr(>|t|)"),

            function (x) signif(x, digits = 3)) %>%

  rename(SE = `Std. Error`,

         t = `t value`,

         p = `Pr(>|t|)`) %>%

  mutate_if(is.numeric, round, digits = 3) %>%

  mutate(p = case_when(

    p < .001 ~ "<.001",

    p < .01 ~ "<.01",

    p < .05 ~ "<.05",

    TRUE ~ as.character(p)))


rownames(freq_coefs) <- c("Intercept", "bilingual", "age_days", "aoi",

                    "bilingual * age_days", "bilingual * aoi", "age_days * aoi",

                    "bilingual * age_days * aoi")


papaja::apa_table(freq_coefs, format.args = list(digits = 3),

                caption = "Coefficient estimates from a linear mixed-effects model pre

                col.names =c("","Estimate","$SE$","$t$","$p$"),

                align=c("l","l","c","c","c"))
```

732   Table 3 shows coefficient estimates from this model and Figure 7 visualizes this model. The

733   significant main effect of age indicated that older monolingual infants looked more frequently

734   at the objects as compared to younger monolingual infants. More centrally, there were both

735   a significant main effect of aoi and an interaction between aoi and age, suggesting that

Table 3

Coefficient estimates from a linear mixed-effects model predicting frequency of shifting gaze towards the congruent AOI.

	Estimate	*SE*	*t*	*p*
Intercept	1.160	0.041	28.500	$<.001$
bilingual	0.066	0.039	1.700	0.09
age_days	0.087	0.025	3.460	$<.01$
aoi	-0.626	0.035	-17.800	$<.001$
bilingual * age_days	0.069	0.039	1.790	0.074
bilingual * aoi	-0.054	0.055	-0.972	0.331
age_days * aoi	-0.104	0.036	-2.920	$<.01$
bilingual * age_days * aoi	-0.029	0.055	-0.525	0.599

736 infants shifted more often to the congruent object as opposed to the incongruent object and

737 that this pattern of looking increased as infants aged. The effect of bilingualism, however,

738 was not significant, and neither were its 2-way interaction with aoi nor its 3-way interaction

739 with age and aoi; this suggests that there was not a reliable difference between bilingual and

740 monolingual infants in the number of times they shifted gaze towards the congruent object.

741 However, the direction of the interaction effect between age and bilingualism, although not

742 significant, would indicate that bilingual infants might show a greater increase in their

743 frequency of looks towards the objects with age compared to monolinguals.

```
d_freq %>%
  group_by(lang_group, object) %>%
  ggplot() +
  facet_grid(.~lang_group) +
  aes(x = age_days, y = n_shift, color = object) +
```

```
geom_smooth(method = "lm", aes(fill=object), se=TRUE) +

ylab("Frequency of shifts towards the AOI") +

xlab("Age in days") +

scale_colour_manual(name = "AOI", values = c("#000000", "#bdbdbd")) +

scale_fill_manual(name = "AOI", values = c("#000000", "#bdbdbd")) +

theme(text = element_text(size = 12), legend.position = "bottom")
```
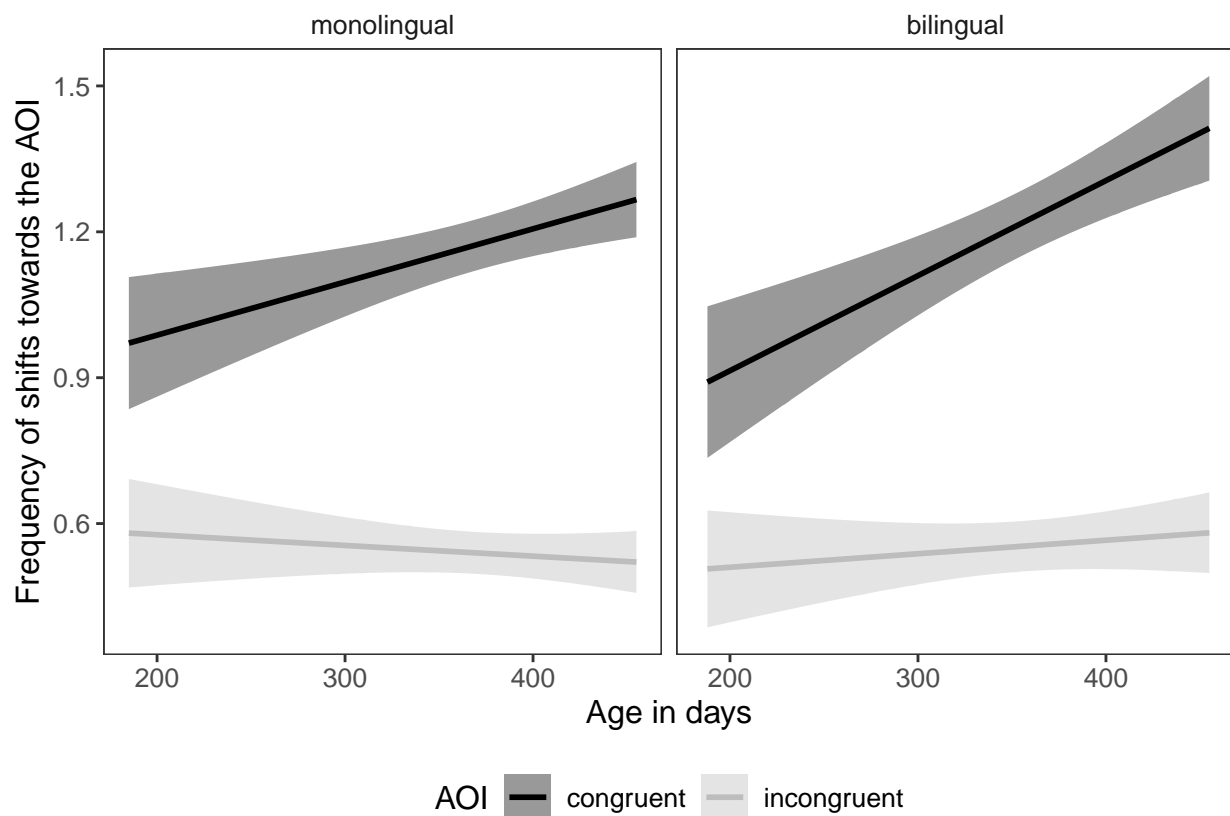

Figure 7. The linear regression model predicting the frequency of shift towards the AOI, with error bars showing 95% confidence interval.

Duration of fixations towards the AOI during the trial. The final model

specification for duration of fixations was:

total_look ~ bilingual * age_days * aoi + (1|lab) + (1|item)

```
duration_lmer <- d_duration %>%

  mutate(age_days = scale(age_days, scale = TRUE)) %>%

  lmer(duration ~ lang_group*age_days*object + (1|lab) + (1|trial_num),

  data = .)


duration_coefs <- summary(duration_lmer)$coef %>%

  as.data.frame %>%

  select(-df)%>%

  mutate_at(c("Estimate","Std. Error", "t value", "Pr(>|t|)"),

          function (x) signif(x, digits = 3)) %>%

  rename(SE = `Std. Error`,

       t = `t value`,

       p = `Pr(>|t|)`) %>%

  mutate_if(is.numeric, round, digits = 3) %>%

  mutate(p = case_when(

    p < .001 ~ "<.001",

    p < .01 ~ "<.01",

    p < .05 ~ "<.05",

    TRUE ~ as.character(p)))


rownames(duration_coefs) <- c("Intercept", "bilingual", "age_days", "aoi",

                 "bilingual * age_days", "bilingual * aoi", "age_days * aoi",

                 "bilingual * age_days * aoi")


papaja::apa_table(duration_coefs, format.args = list(digits = 3),

              caption = "Coefficient estimates from a linear mixed-effects model pre

              col.names =c("","Estimate","$SE$","$t$","$p$"),
```

Table 4

Coefficient estimates from a linear mixed-effects model predicting duration of fixations towards the AOI during the trial.

	Estimate	*SE*	*t*	*p*
Intercept	5.640	0.147	38.400	<.001
bilingual	0.142	0.155	0.919	0.358
age_days	0.345	0.098	3.500	<.001
aoi	-1.690	0.135	-12.500	<.001
bilingual * age_days	0.137	0.152	0.898	0.369
bilingual * aoi	0.225	0.213	1.060	0.289
age_days * aoi	-0.016	0.136	-0.114	0.909
bilingual * age_days * aoi	0.106	0.211	0.501	0.616

```
align=c("l","l","c","c","c"))
```

747 Table 4 shows coefficient estimates from this model and Figure 8 visualizes this model.

748 There were two main effects (age and aoi), but no significant interactions. This suggests that

749 monolingual infants looked longer to congruent versus incongruent objects, and that in

750 general older infants looked longer at the objects than did younger infants. The effect of

751 bilingualism was, however, not significant as a main effect or in interaction with any other

752 factors, suggesting no reliable differences between bilingual and monolingual infants in terms

753 of their duration of looking at the congruent versus incongruent objects.

```
d_duration %>%
  group_by(lang_group, object) %>%
  ggplot() +
  facet_grid(.~lang_group) +
```

```
aes(x = age_days, y = duration, color = object) +

geom_smooth(method = "lm", aes(fill=object), se=TRUE) +

ylab("Duration of fixations towards the AOI") +

xlab("Age in days") +

scale_colour_manual(name = "AOI", values = c("#000000", "#bdbdbd")) +

scale_fill_manual(name = "AOI", values = c("#000000", "#bdbdbd")) +

theme(text = element_text(size = 12), legend.position = "bottom")
```
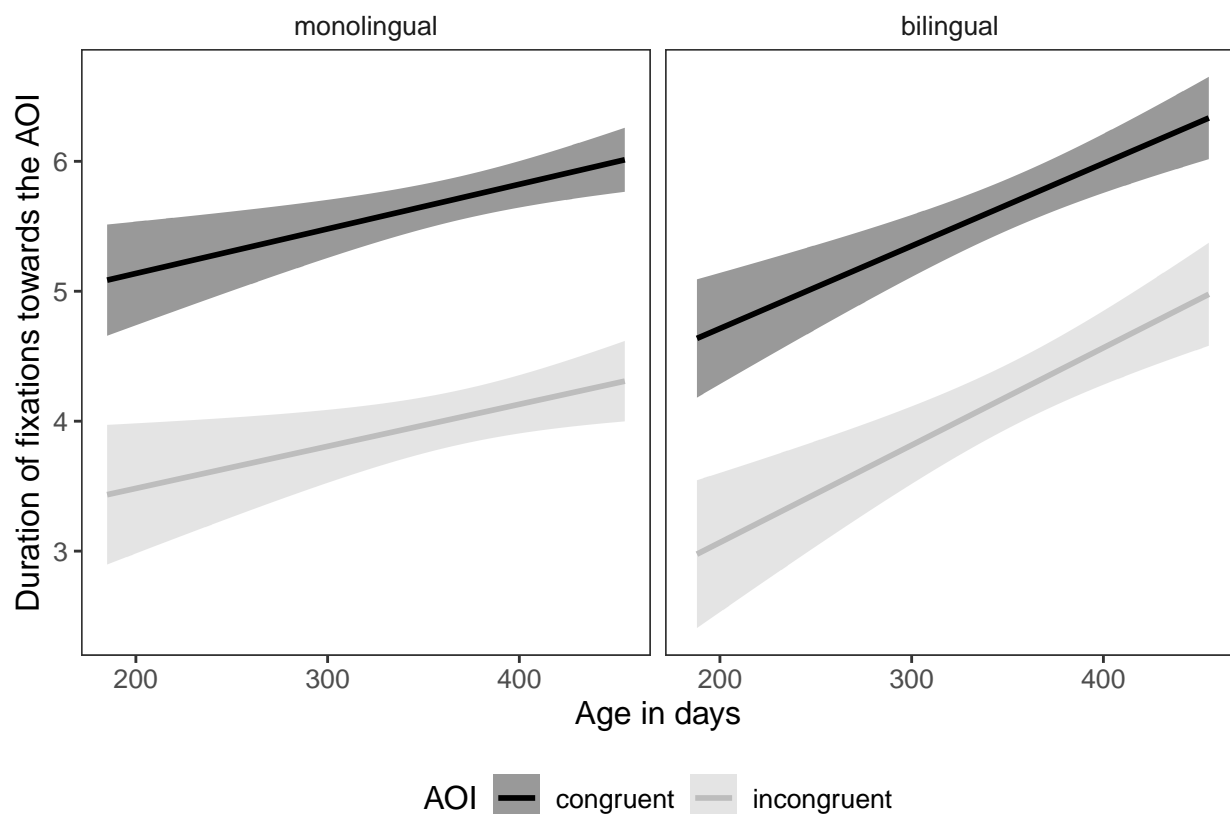

Figure 8. The linear regression model predicting duration of fixations towards the AOI, with error bars showing 95% confidence interval.

754 **Latency.** The final model specification for latency was:

755 latency ~ bilingual * age_days * aoi + (1|subid) + (1|lab) + (1|item)

```
latency_lmer <- d_latency %>%

  mutate(age_days = scale(age_days, scale = TRUE)) %>%

  lmer(latency ~ lang_group*age_days*object+ (1|subid) + (1|lab) + (1|trial_num),

  data = .,

  control = lmerControl("bobyqa")

)


latency_coefs <- summary(latency_lmer)$coef %>%

  as.data.frame %>%

  select(-df)%>%

  mutate_at(c("Estimate","Std. Error", "t value", "Pr(>|t|)"),

            function (x) signif(x, digits = 3)) %>%

  rename(SE = `Std. Error`,

         t = `t value`,

         p = `Pr(>|t|)`)%>%

  mutate_if(is.numeric, round, digits = 3) %>%

  mutate(p = case_when(

    p < .001 ~ "<.001",

    p < .01 ~ "<.01",

    p < .05 ~ "<.05",

    TRUE ~ as.character(p)))


rownames(latency_coefs) <- c("Intercept", "bilingual", "age_days", "aoi",

                  "bilingual * age_days", "bilingual * aoi", "age_days * aoi",

                  "bilingual * age_days * aoi")


papaja::apa_table(latency_coefs, format.args = list(digits = 3),
```

Table 5

Coefficient estimates from a linear mixed-effects model predicting latency between the onset of the actor's head-turn and the moment of first fixation on an object AOI.

	Estimate	SE	t	p
Intercept	7.400	0.051	146.000	$<.001$
bilingual	-0.002	0.055	-0.034	0.973
age_days	-0.124	0.036	-3.470	$<.01$
aoi	0.048	0.056	0.860	0.39
bilingual * age_days	-0.099	0.054	-1.820	0.069
bilingual * aoi	0.074	0.087	0.846	0.398
age_days * aoi	-0.098	0.054	-1.790	0.073
bilingual * age_days * aoi	0.070	0.086	0.810	0.418

```
caption = "Coefficient estimates from a linear mixed-effects model pre
col.names =c("","Estimate","$SE$","$t$","$p$"),
align=c("l","l","c","c","c"))
```

756   Table 5 shows coefficient estimates from this model and Figure 9 visualizes this model. The

757   only significant effect in the model was age, suggesting that older monolingual infants were

758   more rapid than younger monolingual infants in fixating their first look at the congruent

759   objects. There was no significant effect of bilingualism; however, the directions of the

760   marginally-significant interaction effect between age and bilingualism would indicate that

761   bilinguals had a steeper drop in the latency of fixations as they aged compared to

762   monolinguals. Finally, the direction of the interaction between age and aoi suggested that

763   younger monolingual infants made faster first fixations to the congruent objects than to the

764   incongruent objects, but that this latency difference was reduced in older infants. However,

765 the effect of aoi itself was not significant, implying that in general infants did not differ in

766 latency of their first fixation towards the congruent or incongruent objects. Taken together,

767 then, the model reveals that older infants are quicker to make fixations than younger infants,

768 and that language background and object identity do not reliably impact fixation latency.

```r
d_latency %>%
  group_by(lang_group, object) %>%
  ggplot() +
  facet_grid(.~lang_group) +
  aes(x = age_days, y = latency, color = object) +
  geom_smooth(method = "lm", aes(fill=object), se=TRUE) +
  ylab("Latency of fixations towards the AOI") +
  xlab("Age in days") +
  scale_colour_manual(name = "AOI", values = c("#000000", "#bdbdbd")) +
  scale_fill_manual(name = "AOI", values = c("#000000", "#bdbdbd")) +
  theme(text = element_text(size = 12), legend.position = "bottom")
```

769 **Summary of mixed-effects regression.**   Overall, our mixed-effects regression

770 revealed that early gaze-following development is significantly modulated by age-related

771 changes, where older infants showed a more reliable gaze-following ability in every available

772 measure as compared to younger infants. That is, older infants were more accurate and more

773 rapid than younger infants in directing their first gaze towards the congruent objects, and

774 they looked longer and more frequently at the congruent objects than at the incongruent

775 objects. In contrast, bilingualism did not significantly predict infants' gaze-following accuracy

776 and duration of fixations. However, there was a trend where, as they aged, bilingual infants

777 showed a steeper increase in frequency and speed of fixations compared to monolinguals.

778 Regardless of bilinguals' more frequent and more rapid fixations, however, these results most

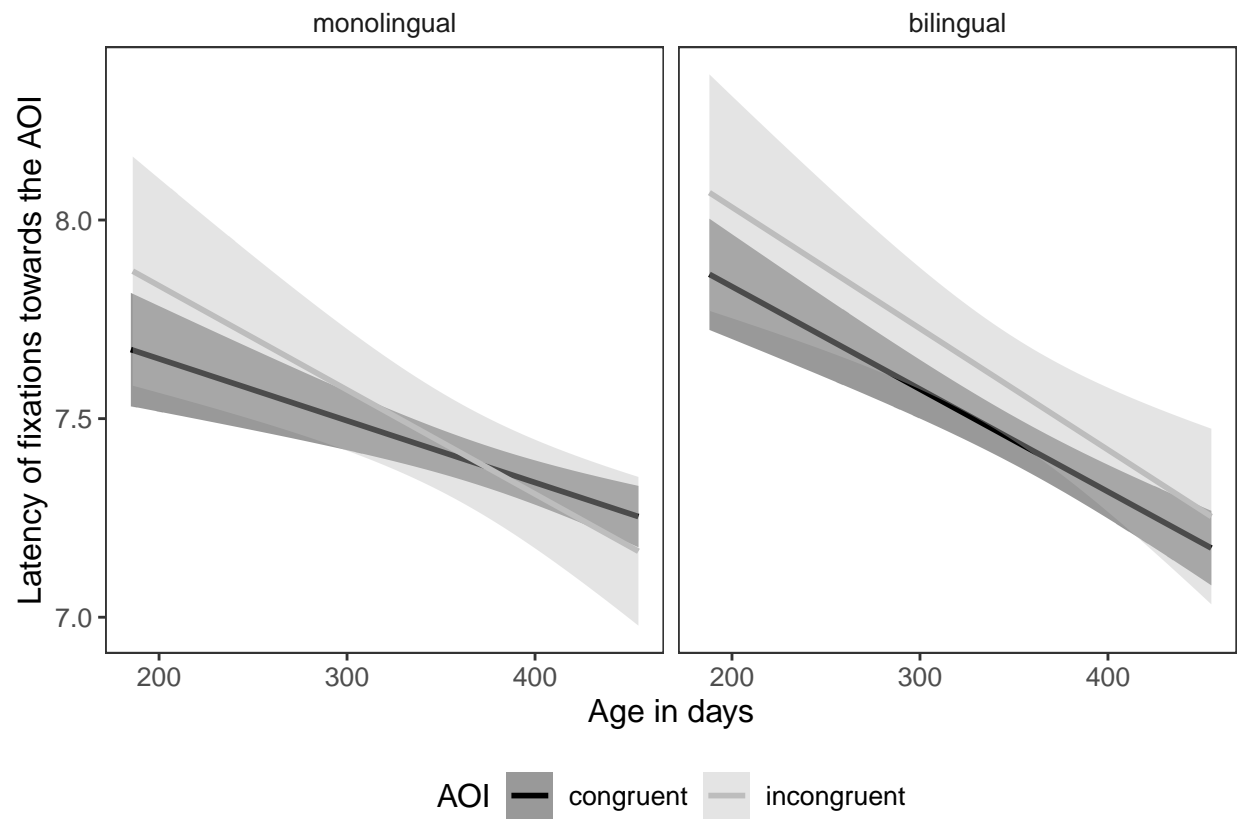779 robustly support the interpretation that monolingual and bilingual infants follow a similar

Figure 9. The linear regression model predicting latency of fixations towards the AOI, with error bars showing 95% confidence interval.

₇₈₀ trajectory of gaze-following development despite their differences in language experience.

General Discussion

₇₈₂   The objective of this study was to launch a large-scale, multi-site study on the effects

₇₈₃ of bilingualism on gaze following at two age groups (6–9 and 12–15 months). Using the

₇₈₄ gaze-following task developed by Senju & Csibra (2008), we investigated the effects of

₇₈₅ bilingual exposure and age on several measures of gaze following (i.e., first look, frequency of

₇₈₆ looks, total duration of looks, and latency). Data were analyzed in accordance with a

₇₈₇ pre-registered analysis plan, comprising a meta-analytic approach and mixed-effects

₇₈₈ regression models. At the outset, we introduced three hypotheses. First, we hypothesized

that all infants would demonstrate an improvement in gaze following towards congruent

objects (i.e., those cued by an adult model) between the two age groups tested. Second, we

hypothesized that bilingual infants would demonstrate more successful gaze following to

congruent objects than monolingual infants, both in terms of accuracy and latency. Finally,

we hypothesized an interaction of age and bilingual exposure on gaze following. We discuss

the first hypothesis concerning all infants, and then turn to the second and third hypotheses

that pertain to effects of bilingualism and its interaction with age.

First, we predicted an effect of age on gaze-following behavior. Overall, infants followed

the gaze of an adult model to the congruent object across a variety of measures. Our

meta-analytic models yielded a medium, but non-significant effect of improved performance

on first-looks and frequency of looks to the congruent object as infants aged. The

meta-analytic models further revealed a significant effect of age on the latency to first look:

older infants were faster to fixate congruent objects than were younger infants. Mixed-effects

models, which allow us to model trial-level behavior and thus gain statistical power, revealed

stronger evidence of age effects: older infants gazed at the congruent object with significantly

greater efficiency and accuracy than younger infants. These findings are consistent with prior

research demonstrating that infants improve their gaze-following as they get older (e.g.,

Butterworth & Jarrett, 1991; Gredebäck, Fikke, & Melinder, 2010; Moll & Tomasello, 2004),

and thus extend this pattern to Senju and Csibra's paradigm. In contrast to our study,

Senju and Csibra tested infants at a single age-group (6 months). Our study demonstrated

that the same infant gaze-following behaviors reported by Senju and Csibra remained

evident between 6 and 9 months and significantly improved by 12 to 15 months.

In addition to demonstrating age-related change, our findings offer a methodological

contribution. With respect to how gaze following is operationalized, our study diversifies the

range of dependent variables through which gaze following can be expressed. Specifically, our

study revealed preferential fixation to the congruent object using first looks and frequency of

looks, as did Senju and Csibra. However, unlike Senju and Csibra, we also found evidence of preferential fixation when fixation duration was used, albeit the duration effects were weaker compared to first looks and frequency of looks. Furthermore, as a complement to accuracy measures, older infants had a tendency towards shorter latencies, which provides a measure of gaze-following efficiency. Overall, this suggests firstly, that the paradigm used by Senju and Csibra in a relatively small sample of 20 infants was replicable in a much larger and more diverse sample of over 300 infants. Secondly, our study provides evidence not only for continuity in gaze-following behavior after 6 months, but additionally evidence for more efficient gaze-following behaviors at age 12–15 months.

The primary objective of our study was to investigate the effects of bilingualism on gaze-following behavior. Our second hypothesis was therefore that bilingual infants would demonstrate greater gaze-following behavior relative to monolingual infants, and our third hypothesis was that this would interact with age. Based on our meta-analyses, there was limited support for these hypotheses. We tested effects of bilingualism across four different dependent variables, using two different analytic techniques. The only evidence we found was in our meta-analysis for latency, which revealed a non-significant trend for slower fixation to congruent objects in bilinguals versus monolinguals in the younger age group, but not in the older age group. In general, however, gaze-following behavior was strikingly similar in monolingual and bilingual infants, suggesting that gaze following is robust to variations in language experience.

At first glance, these findings are seemingly inconsistent with findings from prior studies demonstrating that bilingual children may be more sensitive to eye gaze when learning words than monolingual children (e.g., Brojde et al., 2012; Yow & Markman, 2011). However, the present results are compatible with a recent comparison of bilingual and monolingual infants' gaze-following behavior. Singh, Quinn, Xiao, & Lee (2019) demonstrated similarity in basic gaze-following behavior in monolingual and bilingual groups,

841 using a similar paradigm at 18 months. Similarly, Schonberg, Sandhofer, Tsang, & Johnson

842 (2014) reported that there were no differences between monolingual and bilingual 3- and

843 6-month-olds looking patterns when viewing faces, objects and complex scenes.

844   We offer two possible accounts for the null effects of bilingualism reported here: a

845 conceptual account and a methodological account. Conceptually, in contrast to the present

846 study, prior studies found that when faced with referential ambiguity, bilingual children were

847 better able to use gaze to resolve the conflict and disambiguate the meanings of words (e.g.,

848 Yow et al., 2017; Yow & Markman, 2011). It is possible that bilingual children attend more

849 closely to gaze when gaze truly helps to resolve referential ambiguity. Given that bilinguals

850 likely encounter greater referential ambiguity on account of learning two languages, it is

851 possible that drawing on gaze cues provides a useful strategy for bilingual infants. This is

852 aligned with prior research demonstrating that while monolingual children can resolve

853 referential ambiguity using stored linguistic knowledge (e.g., via mutual exclusivity),

854 multilingual children may need to appeal to other strategies (see Byers-Heinlein & Werker,

855 2009). In the present task, there were no word learning or language comprehension demands,

856 nor was there any ambiguity as to which object served as the target of the adult's gaze.

857 Moreover, gaze cues did not have to be integrated with other sources of information in order

858 to identify the cued object. Instead, this task measured a much more fundamental ability to

859 look at the object looked at by another person. One possibility is therefore that monolingual

860 and bilingual infants begin with similar basic gaze sensitivity and differ in their use of gaze

861 to learn the meanings of words. Effects of bilingualism on word learning may set in closer to

862 18 months, when strategies for referential disambiguation first emerge (Halberda, 2003;

863 Markman, Wasow, & Hansen, 2003). For example, 14- to 17-month-old bilinguals are more

864 sensitive than monolinguals to the objects that a speaker has in her line of sight (Liberman,

865 Woodward, Keysar, & Kinzler, 2017).

866   It is also possible that methodological differences contribute to discrepancies between

our findings and prior studies. Prior studies demonstrating bilingual advantages have used much smaller sample sizes, ranging from 16-24 children per group. Two core advantages of large-scale, pre-registered reports is i) that they have the potential to investigate whether effects are replicated in larger, diverse samples with a standardized protocol (Frank et al., 2017) and ii) that they are somewhat spared from possible confirmation biases in the publication process, which often favor evidence for a bilingual advantage (see de Bruin et al., 2015). It is possible that prior evidence of bilingual advantages in gaze sensitivity are not as replicable or stable than smaller-scale studies would suggest. This is not intended as a criticism or indictment of any prior study, but rather as a reference to the promises of methodological standardization, predetermined protocols, and increased statistical power.

Although we did not observe striking differences between monolinguals and bilinguals in gaze following ability, we did observe some suggestive differences between monolinguals and bilinguals in their overall attention to the objects (both congruent and incongruent). Compared to monolinguals, bilinguals showed some evidence of steeper changes in the frequency and latency of fixations to congruent objects in general as they aged, although these findings were not particularly statistically robust. These tendencies would seem consistent with other studies suggesting that allocation of attention is sensitive to environmental experience from early in life. For example, sighted infants of blind parents showed a decrease in gaze-following attention compared to the control infants; furthermore, this difference increased between 6–10 and 12–16 months of age (Senju et al., 2015). Conversely, deaf 7- to 20-month-old infants of deaf parents showed enhanced gaze-following attention to visual communicative signals, with the younger infants showing more robust gaze-following behavior relative to hearing infants (Brooks, Singleton, & Meltzoff, 2020). Overall, subtle changes in selective attention to objects early in development, as might be the case here with bilingual infants' tendency to look more frequently and more rapidly at objects, may be relevant for everyday processing of socially relevant information and subsequent language outcomes. However, given that our findings were not predicted and

failed to reach statistical significance, this pattern will need to be replicated.

Challenges and Limitations

Here, we address some of the challenges and limitations of the present study. We begin broadly with challenges common to other studies launched under the ManyBabies initiative (Byers-Heinlein, Bergmann, et al., 2020). To some extent, these challenges may reflect "teething problems" associated with adapting more traditional individual laboratory studies to cross-laboratory collaborative studies. At the outset, it became clear that participating labs had different protocols for collecting data, surveying language background, and administering studies. We encountered several procedural challenges in determining how to work with differences in equipment, personnel, and other resources available to different investigators. A very basic difference in the present study was how different laboratories tracked gaze following: some used manual video recording while others used eye-trackers. Even within the labs with eye-trackers, there was likely considerable variation in how robustly different eye-trackers captured gaze data. Similarly, there was variation in the quality of video-records obtained by labs that did not use eye-trackers. This provides one of several examples where efforts towards methodological standardization (or "streamlining") cannot wholly eliminate effects of methodological variation across labs. While some of this variation can be captured in data processing (in our case, analysis scripts had to be adapted to each eye-tracking setup), other sources of variation cannot easily be identified or controlled. In this way, sources of unexplained error variance in multi-site large-scale studies are likely different from those obtained in single-laboratory studies, which can affect the interpretation of findings.

A second consideration relates to analyses. We pre-registered two analytic approaches: meta-analysis and mixed-effects regression models. However, these two approaches pointed to different conclusions in some cases, and thus made interpretation challenging. In general,

we interpret these differences in light of the additional statistical power provided by the regression models, which were ultimately more sensitive and revealed more nuance in our data set. While this is likely due to averaging across groups of infants in the meta-analytic models which decreases statistical power relative to linear mixed-effects models, it raises questions for interpretation. For example, we hypothesized effects of age, which were more evident in the mixed-effects models than in the meta-analyses. We hope that by transparently pre-registering and reporting all analyses, readers will feel more convinced by our interpretations, or at least be more able to draw their own conclusions.

Finally, we acknowledge that in spite of having recruited a geographically diverse sample, our samples were likely similar in several ways. First, our samples were all drawn from developed, Westernized countries. Within each country, participation was limited to families who were available and interested to come to a university laboratory, likely limiting socio-economic diversity. Our sample probably included mainly infants of higher socio-economic status, as is typical in laboratory-based developmental research. We had no participating labs from Latin America, Africa, South Asia, East Asia or the Middle East. Therefore, the typical limitations of convenience sampling no doubt applied to our study. This is relevant to studies of gaze following preceded by eye contact, as ethnographic reports of parent-infant interactions reveal considerable cross-cultural variation in the extent to which adults engage in eye contact with their infants (LeVine & Norman, 2001). In some societies such as the Gusii of Kenya, eye contact with infants is far less common. For example, in 6-month-old infants, eye contact occurs in less than 10% of interactions between infants and caregivers (Tronick, 2007). Similarly, in some cultures, such as the Nso in Northern Cameroon, parents blow into the eyes of infants to actively avoid eye contact (LeVine & LeVine, 2016). As a result, there is reportedly much less intentional eye contact between adults and infants in the first year of life than is often reported in Westernized societies (see LeVine et al., 1994). Examples of reduced eye contact are primarily drawn from non-Western rural societies, which were not represented in our study. Consequently,

infants' responsiveness to gaze-cuing may depend on its frequency and functionality in their natural environment. For example, one study in a rural small-scale society in Tanna island in Vanuatu found evidence of gaze following in infants as young as 5 to 7 months of age (Hernik & Broesch, 2019), despite reports of relatively lower frequency of face-to-face mother-infant interactions in the same community (Little, Carver, & Legare, 2016). Having greater geographical and socioeconomic variation within participating labs in the current study would have helped to qualify evidence of uniformity in gaze following across infants being brought up in diverse cultural contexts.

Summary

This study forms part of a groundswell of large-scale, multi-lab initiatives all working towards the common goal of investigating generalizability and replicability of core findings in infant cognition (c.f., ManyBabies Consortium, 2020; Byers-Heinlein, Bergmann, et al., 2020; Byers-Heinlein, Tsui, et al., 2020). Sampling 322 infants distributed across 8 countries and 3 continents, this study provides confirmatory evidence for the replicability and generalizability of past evidence for infants' sensitivity to gaze cues. Given the developmental significance often ascribed to infant gaze following (see Moore, 2008), there are clear scientific gains in knowing that infant gaze-following behaviors withstand the kind of geographical and cultural variation captured in our sample. That gaze-following does not appear to be influenced by bilingualism suggests that fundamental gaze sensitivity also withstands variation in language exposure. The results of the current study point to striking uniformity in how different samples respond to gaze cues in infancy, at least within a westernized cultural context. The findings of this study speak to the stability of infant gaze-following behaviors, but also inform the vast body of literature that invokes gaze following as a critical social response upon which much of later language learning depends (see Baldwin, 1995; Brooks & Meltzoff, 2014).

Author Contributions

Authorship order reflects the first author and the final author as project leads, authors 2-4 as the core analysis team, and authors 5-25 listed in alphabetical order by last name. Detailed contributions are as follows: KBH, ÁMKá, LS contributed to the study concept. KBH, RB, ÁMKá, CLW, LS contributed to the study design. KBH contributed to the final protocol. KBH contributed to study documentation. KBH, LS contributed to study management. KBH, RB, AB, MC, SD, AG, NGG, JFH, MH, MJó, ALR, CLW, UL, LL, CN, CEP, JRH, MS, CW, LS contributed to data collection. KBH, AKB, JFH, MJó, MS, RKYT, DR, IV contributed to data management and analysis. KBH, RB, AKB, NGG, JFH, CLW, DR, IV, LS contributed to the Stage 1 manuscript. KBH, AKB, JFH, JRH, NSG, RKYT, LS contributed to the Stage 2 manuscript.

Conflicts of Interest

The authors declare that there were no conflicts of interest with respect to the authorship or the publication of this article.

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Disclosures

Preregistration

Our manuscript was reviewed prior to data collection; in addition, we registered our instructions and materials prior to data collection osf.io/2ey3k/.

Data, materials, and online resources

All materials, data, and analytic code are available at osf.io/2ey3k/.

Reporting

We report how we determined our sample size, all data exclusions, all manipulations, and all measures in the study.

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