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Effects of Environmental Diversity on Exploration and Learning: The Case of Bilingualism

Leher Singh[1], Rachel Barr[2], Paul C. Quinn[3], Marina Kalashnikova[4, 5], Joscelin Rocha-Hidalgo[6], Kate Freda[2], and Dean D'Souza[7, 8]

[1] Department of Psychology, National University of Singapore
[2] Department of Psychology, Georgetown University
[3] Department of Psychological and Brain Sciences, University of Delaware
[4] Basque Center for Cognition, Brain and Language, San Sebastián, Spain
[5] Ikerbasque, Basque Foundation for Science, Bilbao, Spain
[6] Department of Psychology, Pennsylvania State University
[7] Department of Psychology, City, University of London
[8] School of Psychology, Cardiff University

Bilingual environments provide a commonplace example of increased complexity and uncertainty. Learning multiple languages entails mastery of a larger and more variable range of sounds, words, syntactic structures, pragmatic conventions, and more complex mapping of linguistic information to objects in the world. Recent research suggests that bilingual learners demonstrate fundamental variation in how they explore and learn from their environment, which may derive from this increased complexity. In particular, the increased complexity and variability of bilingual environments may broaden the focus of learners' attention, laying a different attentional foundation for learning. In this review, we introduce a novel framework, with accompanying empirical evidence, for understanding how early learners may adapt to a more complex environment, drawing on bilingualism as an example. Three adaptations, each relevant to the demands of abstracting structure from a complex environment, are introduced. Each adaptation is discussed in the context of empirical evidence attesting to shifts in basic psychological processes in bilingual learners. This evidence converges on the notion that bilingual learners may explore their environment more broadly. Downstream consequences of broader sampling for perception and learning are discussed. Finally, recommendations for future research to expand the scientific narrative on the impact of diverse environments on learning are provided.

Public Significance Statement
This article focuses on how bilingual experience, as a source of environmental diversity, determines how learners attend to their environment. The premise of the article is that more diverse environments are more complex and may instill different modes of learning and attention, fostering greater attention to novelty.

Keywords: bilingualism, attention, visual perception, diversity, novelty preference

Leher Singh https://orcid.org/0000-0001-9423-4956

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Correspondence concerning this article should be addressed to Leher Singh, Department of Psychology, National University of Singapore, 9 Arts Link, Singapore 17 572, Singapore. Email: psyls@nus.edu.sg

In order to navigate and successfully learn from the environment, infants and children must allocate their attention selectively to the vast array of stimuli present in their surroundings. In multiple domains, studies have demonstrated that early in life, naïve learners do not attend equally to all sources of information but come to prefer familiar information based on prior experience. For example, infants begin to visually prefer faces of the gender corresponding to their primary caregiver (Quinn et al., 2002) and faces from their own race (Kelly et al., 2005). They also express early auditory preferences for their own language (Bosch & Sebastián-Gallés, 1997; Moon et al., 1993) and for musical styles that are common within their environment (Soley & Hannon, 2010).

The notion that infants initially orient toward familiar information within their environment is aligned with and often explained by prevailing models of infant attention (e.g., Hunter & Ames, 1988). These models are predicated on the assumption that upon first encounter with a stimulus, the infant seeks to match the stimulus with an existing memory representation (Sokolov, 1963). Only when the stimulus reaches some threshold of similarity with a stored representation is attention then deployed elsewhere (Roder et al., 2000). This account of early attention posits that infants prioritize recurring information in their environment. In laboratory studies, this is expressed as a familiarity preference. An early familiarity preference has been argued to allow infants to extract relevant and significant information from their environment (Houston-Price & Nakai, 2004; Hunter & Ames, 1988).[1]

As infants acquire greater experience, they then begin to explore novel (nonrecurring) information to a greater extent (Hunter et al., 1983). This is consistent with the notion that a novelty preference follows from an initial orientation toward familiarity (Roder et al., 2000; S. A. Rose et al., 1982). The issue of when early learners orient toward familiarity or novelty remains a matter of ongoing scientific interest with different underlying theoretical accounts. For example, following Bowlby (1988), infant looking has been thought to reflect the operation of complementary systems for attachment security (familiarity orientation) and exploration-based mastery of the environment (novelty orientation) (Quinn et al., 2013; see also Bischof, 1975). Relatedly, familiarity versus novelty orientations may be early precursors of tendencies toward exploitation and exploration of information (Gopnik, 2020).

In interrogating the determinants of infant attention, researchers rely heavily on looking-time differences between contrasting stimuli to make inferences about what infants know, perceive, and learn (Csibra et al., 2016). These inferences are often based on variation in the magnitude of looking time across different stimuli. Using looking time differences, infant attention has been used to query many dimensions of early perception and learning in different domains. Implicit in the use of infant attention to reveal latent developmental processes is the notion that infants direct their attention in a manner that optimizes learning (C. Kidd et al., 2012). However, the interpretation of looking time is complex: As noted above, infants can express preferences for familiar or novel stimuli. As such there remains considerable uncertainty around the conditions under which infants demonstrate either type of preference (Kosie et al., 2023).

In theoretical accounts of infant attention, researchers have advocated for a relationship between prior exposure, developmental stage, and task difficulty as codeterminants of infant attention. A predominant model of infant attention—the Hunter and Ames model—posits that these factors work in concert to produce familiarity versus novelty preferences (Hunter & Ames, 1988). Thus far, this model has been used to explain and predict findings in many areas of infant processing, such as speech segmentation, object memory, face recognition, musical perception, and memory for numbers amongst other areas (see Kosie et al., 2023). However, a major limitation is that this debate has centered heavily around endogenous determinants of attention (Hunter et al., 1983; Kosie et al., 2023). There has been little focus on how infants' natural environments—and the diversity therein—might modulate infants' attentional preferences. Given the centrality of looking time measures in infant attention, it is critical to understand how early preferences are modulated by environmental factors. The dearth of work on exogenous determinants of infant attention may reflect an interpretation that the experimental tasks that are commonly used (e.g., visual habituation; visual preference) are stable across individuals and in equal measure, to a tendency to underreport experiential factors in infant research (Singh, Cristia, et al., 2023). These factors make it challenging to determine how attentional measures may vary based on environmental experience. Greater reporting of experiential factors and expansion of the repertoire of tasks commonly used to measure infant attentional processes would elucidate the links between experience and exploration.

The question of whether environmental diversity influences the allocation of infants' attention relates to empirical studies demonstrating that diversifying exogenous experiences may modify infants' attentional biases. In particular, greater diversity may lead to a greater orientation toward broad exploration and novelty within the environment, modifying the direction of infants' attentional preferences. This, in turn, appears to be associated with greater flexibility and plasticity in attention. For example, infants with early biracial exposure—at an individual level—do not show an own-race preference at 3 months of age (Bar-Haim et al., 2006), unlike those with primarily monoracial exposure (Kelly et al., 2005, 2007; Liu et al., 2015; also see Gaither et al., 2012, for face processing differences between monoracial- and biracial-exposed infants). In addition, infants with multiracial exposure at a societal level also do not demonstrate an own-race preference, but instead express an other-race preference, a pattern which is even more pronounced for those with individual contact with other races (Singh, Phneah, et al., 2022; Singh, Rajendra, & Mazuka, 2022). Analogous effects of environmental diversity are observed in the domains of language and music, where diverse environments are associated with reduced familiarity preferences. For example, bilingually exposed infants respond preferentially to foreign languages over their own languages (Bosch & Sebastián-Gallés, 1997), express a reduced native language preference (Byers-Heinlein et al., 2010), and show prolonged sensitivity to nonnative sounds (Singh & Tan, 2021). In the music domain, early exposure to the music of other cultures reorients infants toward novel musical patterns originating outside of their culture (Hannon & Trehub, 2005). The preference for novel stimuli associated with environmental diversity even extends to languages and racial groups that infants have reportedly never encountered (Singh, 2018; Singh, Phneah, et al., 2022; Singh, Rajendra, & Mazuka, 2022).

These studies converge on the notion that very basic exploratory behaviors that drive adaptation and learning may vary due to

[1] We do not suggest that all stimuli are initially neutral and recognize that some stimuli may be encountered in utero (e.g., Byers-Heinlein et al., 2010) or may elicit biologically driven preferences early in life (e.g., Morton & Johnson, 1991).

environmental diversity. Such effects may not be apparent in the literature due to a focus on relatively homogenous samples that may overrepresent sameness of experience. Biases favoring monoexperiential samples may have driven a particular narrative around early exploration that does not generalize to more diverse environments. For example, studies demonstrating own-race preferences early in life have mainly drawn from monoracial environments (e.g., Kelly et al., 2005, 2007; Liu et al., 2015). Similarly, studies demonstrating early own-language preferences have typically drawn from monolingual environments (e.g., Moon et al., 1993). In general, sampling practices in infant research have overrepresented infants from limited environments and have centered on traditionally monolingual regions of North America and Western Europe (Singh, Cristia, et al., 2023). It is possible that more flexible pathways to learning and exploration emerge within more diverse environments. Expanding the study of the range of experiences available to infants can inform our understanding of the flexibility of the human psychological repertoire and its adaptation to the vast range of experiences and environments within which infants are raised.

A commonplace example of environmental diversity is the bilingual experience. Although underrepresented in psychological research (E. Kidd & Garcia, 2022), most children worldwide are raised with more than one native language (Ansaldo et al., 2008; Ellajosyula et al., 2020; Giovannoli et al., 2020; Grosjean, 2010, 2013). Bilingual experience is, therefore, a very relevant form of diversity for most individuals and understanding the psychological impact of such experience on development is central to a more representative science of early human development. In several respects, bilingualism provides unique insights into the effects of environmental diversity on psychological processing. First, children raised with more than one language early in their lives are immersed in the language(s) spoken in their environment. Notably, early bilingualism reflects a form of diversification that is not selected by the individual, but which selects the individual via parents, general societal norms, government policy, or some combination of factors. Unlike other forms of diversity which may be the product of individual selection, where it is difficult to tease apart the effects of prior motivation on behavior, early bilingualism is often unique in that it happens to a learner.

Second, bilingualism is unique in its complexity of diversity. Although bilingualism commonly refers to dual language use, bilingual experiences are nested within a range of other diversifying experiences, such as biculturalism and bidialectalism, as language use is necessarily grounded in a social context. Therefore, bilingualism provides an opportunity to examine a relatively rich source of diversity expressed across different facets of human experience. Effects of bilingual experience are also multidimensional in nature. Specifically, although bilingual exposure typically involves linguistic experience with two languages, there are both proximate and distal effects on psychological development. Proximate effects relate to the effects of bilingual experience on language processing (for a review, see Sebastián-Gallés & Santolin, 2020). However, there are more distal effects on basic developmental processes that may, in turn, influence higher-order forms of learning. The notion that language use and exposure can influence central cognitive processes has captured the attention of psychologists as it provides a unique example of cross-domain transfer of language experience to basic cognition (Bialystok, 2015).

In this review, we introduce a new framework for organizing our knowledge of early bilingual psychological development that is driven by recent evidence, drawing from both behavioral and neural models of adaptation to experience. Our framework is consistent with broader theories emphasizing the role of experience in cognitive development, inclusive of selectionism (Changeux, 1985; Edelman, 1987), interactive specialization (Johnson, 2011), and developmental niche construction (Flynn et al., 2013), although such theories have tended to envision monolithic environments for an individual's development. We structure our framework in terms of the necessary adaptations that bilingual learners must make to learn two linguistic systems, drawing on evidence from different laboratories, bilingual populations, and methodologies. In each of these areas of adaptation, we present empirical evidence illustrating how bilingual attention may attune to and align with the specific demands of increased environmental diversity, resulting in greater flexibility and plasticity. Finally, we chart a roadmap for future directions in empirical research.

Adaptations to Bilingual Experience

We discuss three adaptations to bilingual experience that may facilitate the uptake of multiple languages. At the outset, we note our focus on the early and simultaneous acquisition of two languages rather than on the sequential acquisition of two languages. This focus reflects the language learning environment in which most infants around the world are immersed (Grosjean, 2010). Furthermore, we frame these adaptations as forms of attunement to bilingual experience with the explicit qualification that these adaptations may reflect generalized effects of environmental complexity or diversity rather than unique effects of bilingualism. Lastly, we do not claim that bilingual environments are unique or special: To our knowledge, there is no evidence that the developing brain defaults to monolingualism (and given the global prevalence of bilingual speakers, one could argue that the term "adaptation" applies instead to monolingual environments).

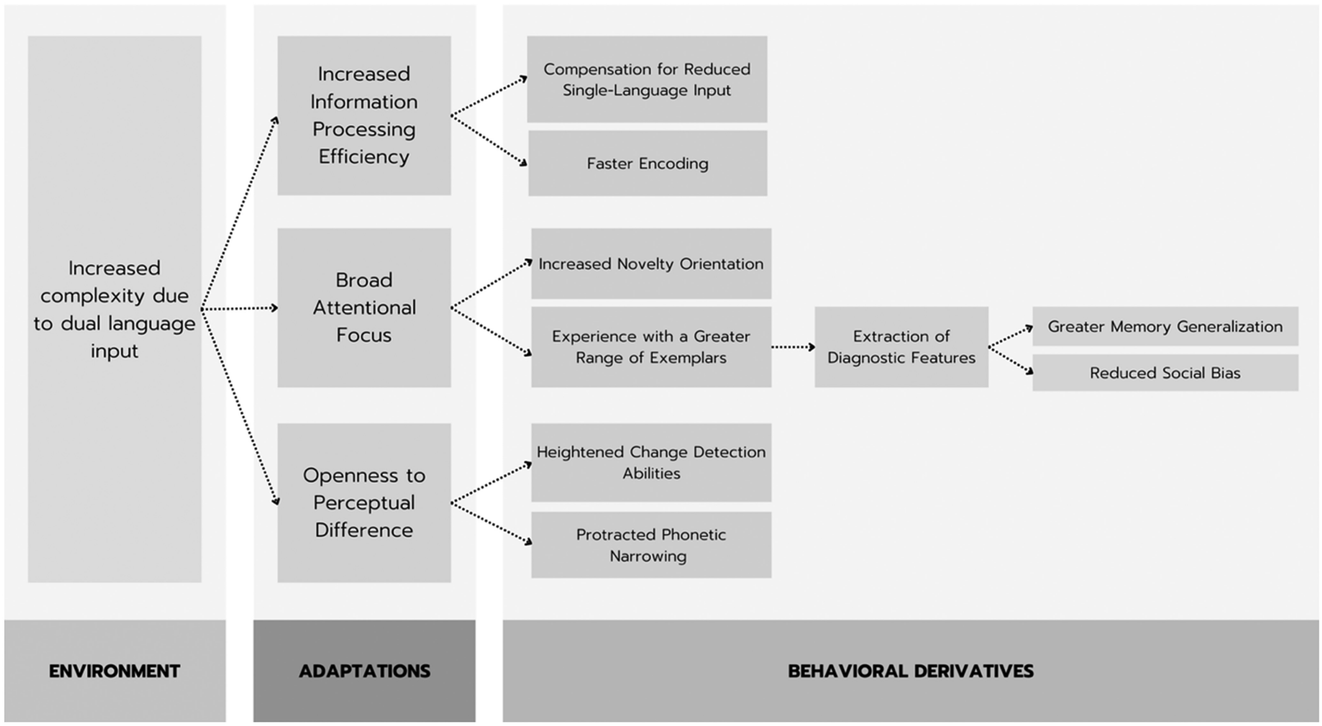
A summary of our framework is shown in Figure 1. It illustrates the environmental challenge posed by learning two languages, the adaptations to that challenge, and their behavioral derivatives. The adaptations and behavioral derivatives will be described in the following sections of the article, with Figure 1 serving as an organizing structure. In this article, we will draw on empirical evidence and connect three adaptations (and their behavioral derivatives) to processing two language streams: (a) increased information processing efficiency, (b) broad attention focus, and (c) openness to perceptual difference. We qualify this framework by stating that further research is needed to confirm causal pathways between nodes of the framework.

Adaptation I: Increased Information Processing Efficiency—Doing More With Less

Bilingually exposed infants receive less input in each language than monolingually exposed infants in one language (e.g., Garcia-Sierra et al., 2016). At the same time, bilingual learners are faced with expectations of native language proficiency in each language. This observation raises the question of how early bilingual learners navigate reduced, but more complex and variable, input to learn two languages to native proficiency levels.

Empirical studies demonstrate links between quantitative variation in bilingual environments and uptake of each language. In particular, the amount of single-language exposure in bilingual learners predicts the amount of single-language uptake (Hoff, 2018;

Figure 1
A Summary of Bilingual Adaptations and Developmental Consequences



Unsworth, 2016), mimicking dose–response relations in monolingual learners (Hurtado et al., 2008). In monolingual learners, reduced input presents developmental risk (Weisleder & Fernald, 2013). Simply hearing less of each language might, therefore, be expected to introduce risk to language learning in bilingual learners. However, this is not the case. Although bilingual children do progress through single-language milestones at a slower rate than their monolingual peers in the early stages of language development (Hoff & Core, 2013), they often do acquire two languages to native levels without significant modifications to the timeline of acquisition of words, phrases, and sentences. A reduced ratio of the quantum of input to the quantum of uptake in bilingual learners may indicate increased information processing efficiency in bilingual learners.

Measurement of information processing efficiency in infancy has embraced a very basic encoding model, visual habituation, which reflects the process by which infants encode and adapt to novel information. Visual habituation is commonly expressed by a progressive reduction in visual attention to a stimulus upon repeated presentation (Colombo, 1993). Measurement of processing efficiency using visual habituation has had a longstanding presence in infant research (see Sokolov, 1963) and still serves as the primary mechanism by which infant learning is assessed in laboratory settings (Oakes, 2010; Sirois & Mareschal, 2002).

In typical infant visual habituation paradigms, infants are repeatedly presented with a single stimulus, and fixation time progressively decreases to a low asymptote (R. F. Thompson & Spencer, 1966). Following habituation, infants demonstrate a preference for a change in stimulus, referred to as a novelty preference. A novelty preference indicates that infants recognize the novel stimulus as distinct from the habituation stimulus (Colombo et al., 2010). Habituation behaviors in infancy have long-term predictive validity, relating to vocabulary size in toddlers (Colombo et al., 2010), verbal components of intelligence quotients (D. H. Rose et al., 1986), and full-scale intelligence quotients (McCall & Carriger, 1993; L. A. Thompson et al., 1991).

In a study on the effects of bilingualism on information processing, Singh et al. (2015) tested 6-month-old Singaporean infants exposed to either one or two languages on a visual habituation task. Infants were from heterogenous bilingual and monolingual backgrounds and were matched on socioeconomic factors (parental education and income). First, infants were exposed to an image of a wolf or a bear. The same image was presented repeatedly, and fixation to the image was logged. The infants were then presented with the visual image that they had just seen, but it was paired with a novel image. The images (the wolf and the bear) were relatively similar, requiring infants to be sensitive to color and subtle featural information to differentiate them. The authors reported that monolingual and bilingual infants demonstrated similar levels of total fixation to the habituation stimulus. However, the groups differed in how much their attention declined over the habituation session and the slope of their habituation function (fixation to the familiarization image plotted by trial). Bilingually exposed infants showed both a larger decrement in attention over the habituation phase and a steeper gradient of the habituation function. In addition, only bilingually exposed infants demonstrated preferential fixation to the novel stimulus during the comparison phase. These outcomes indicate that the greater rate of information processing did not compromise information encoding but was associated with stronger recognition memory for the target stimulus.

Singh et al. (2015) provided evidence that information may be processed more efficiently in infants exposed to multiple languages, providing one mechanism by which bilingual learners may compensate for reduced single-language information to attain native proficiency in two languages. However, in addition to faster encoding, the study revealed increased orientation toward novel information during the paired-comparison (test) phase. This finding raises the question of whether bilingual infants distribute attention more broadly, scanning both familiar and novel information within their environment. Broad informational sampling may be an adaptation to a complex environment by allowing learners to more effectively abstract underlying structure. In the next section, we discuss this specific adaptation in relation to empirical evidence pointing to broad informational sampling in bilingual learners.

Adaptation II: Broad Distribution of Attention Across Familiar and Novel Stimuli in the Service of Learning

In addition to receiving less single-language input, bilingual infants receive more variable input. At each tier of the language code (phonology, semantics, syntax, pragmatics), bilingual input contains different regularities and rules (Byers-Heinlein & Fennell, 2014). In addition, bilingual environments also contain language mixing and switching (Genesee & Nicoladis, 2006). The impact of this complexity and variability is that learners must negotiate language input that is less predictable and contains greater uncertainty. In the face of heightened uncertainty, it may benefit learners to attend more broadly to variable sources of information within their environments in order to identify relevant (or diagnostic) cues (see Figure 1).

This suggestion aligns with theoretical accounts of domain-general organizational principles that allow naïve learners to distill input to identify relevant cues in relation to variability in the input (Bhatt & Quinn, 2011). The presence of increased variability in the environment introduces indeterminacy and uncertainty and could make the initial phases of learning more challenging (Raviv et al., 2022). However, attending to and harnessing available sources of variability may facilitate organization of input into meaningful categories. A possible analog from the domain of vision is the finding that infants presented with two different visual classes more readily formed category representations than infants presented with just one visual class (Quinn, 1987). This result provided empirical evidence that experience with multiple classes allowed infants to extract not only what was common within each class, but also what was distinctive about each class.

Beneficial effects of variability on learning have been attested in multiple domains including formation of intermodal mappings (Vukatana et al., 2015), linguistic categorization (Singh, 2008), and face processing (Balas & Saville, 2015). Across a range of domains, tasks, and populations, these findings converge on the suggestion that while greater variability may increase the complexity of the input, it may also facilitate the abstraction of invariant (diagnostic) cues. In this way, increased variability may both promote extraction of relevant information (which may stand out as invariant against the higher variability, Gibson, 1979) and the generalization of acquired information to novel contexts. Bilingual environments—in representing greater variability—may facilitate learning of invariant cues and subsequent generalization.

An attentional focus on recurrent information in a variable environment may not allow for variability to be harnessed in the service of learning. In other words, in order to benefit from environmental variability, learners must attend broadly within their environment. Recent studies have examined whether bilingualism is associated with more variable patterns of attentional allocation. These studies suggest that bilingual exposure is associated with an increased tendency to (a) disengage from recurring information to engage with novel information, (b) attend more broadly to information within the environment, and (c) generalize learned information to novel contexts, defined as transferring learned information to previously unencountered stimuli. We address each area of research in turn.

The Impact of Variability on the Distribution of Attention

The distribution of attention within bilingual and monolingually exposed infants was recently investigated by D'Souza et al. (2020). The authors tested bilingual and monolingually exposed infants between 7 and 9 months originating from varied language backgrounds in the United Kingdom. Monolingual and bilingually exposed infants were matched on a composite measure of socioeconomic status (SES; parental education, occupation, income, place of residence). The authors tested infants on a range of tasks, two of which were designed to investigate allocation of attention and detection of change. In the allocation of attention tasks, the authors presented infants with a central stimulus and a peripheral stimulus. In some trials, the two stimuli overlapped in time, and in some, they were presented asynchronously. The authors measured the latency between the presentation of a peripheral stimulus and the amount of time infants took to shift their gaze to the peripheral stimulus. Using a subset of infants who provided the best quality data (i.e., a higher number of valid trials), the authors found that the bilingually exposed infants were faster to disengage and shift attention from the central stimulus to the peripheral stimulus than the infants growing up exposed to one language. Moreover, the speed of disengagement was greater for infants who had greater second-language exposure. That is, bilingual infants were quicker to disengage from familiar information to engage with novel information (see Figure 1).

In addition to disengagement, D'Souza et al. (2020) investigated the rate at which 7- to 9-month-old infants switched attention between two stimuli presented simultaneously. Infants viewed two stimuli (e.g., two male heads), one of which gradually morphed into a novel stimulus, and the authors measured infants' switches between them. Compared with monolingually exposed infants, bilingually exposed infants switched attention more between the two stimuli. In addition, when comparing switching behavior in the current experiment with the speed of disengagement in the initial experiment of D'Souza et al. (2020) (i.e., the same infants were tested in both tasks), the authors reported a negative correlation for bilingually exposed infants (e.g., those who were faster to disengage showed greater switching), but no association for the infants growing up exposed to one language.

A second set of studies points to a greater novelty orientation in bilingual infants. In a recent investigation, Singh et al., (2023) examined infants' preferences for familiar versus novel information. Testing 5- to 9-month-old monolingually and bilingually exposed infants from Spain and Singapore matched on SES, infants' preferences for novelty were assessed using a visual preference paradigm. Using an adaptation of a paradigm developed by Fantz (1964), infants were presented with two stimuli side-by-side over a series of trials. In each trial, one stimulus remained constant (familiar stimulus), and the other stimulus changed (novel stimulus). Over the succession of trials, bilingually exposed infants showed a persistent preference for the changing stimulus. In contrast, monolingually exposed infants demonstrated an initial null preference, followed by a novelty preference as the experiment progressed. The latter resembles Fantz's original data, providing additional evidence that bilingual infants initially have a broader attentional focus. In addition, the extent of infants' initial novelty preferences was positively correlated with the extent of second-language exposure (see Rocha-Hidalgo et al., in prep for similar findings in 18-month-olds from the United States).

A related study providing further evidence supporting the idea that bilingually exposed infants demonstrate an increased orientation to novelty comes from Kalashnikova et al. (2021). In a replication attempt of Kovács and Mehler (2009), a study where 7-month-old bilingually exposed infants were reported to have attentional control advantages, Kalashnikova et al. (2021) did not replicate the attentional control advantages observed by Kovács and Mehler (2009) in a sample of 7-month-old infants. In the paradigm used by both sets of investigators, the demonstration of attentional control rested on infants' ability to correctly anticipate the location of a visual reward following an auditory or visual cue, which appeared on one side of the screen for the first half of the trials and on the opposite side of the screen for the last half of the trials. Using this paradigm, Kalashnikova et al. (2021) reported that even in cases when bilingually exposed infants were less likely to anticipate the location of the reward correctly compared to monolinguals, once the visual reward appeared on the correct side, they fixated it as fast as monolinguals. This result suggests an increased preference for the novel visual reward relative to monolingual infants.

Overall, bilingual infants show increased novelty orientation and faster encoding (Figure 1). In combination, the evidence converges on the suggestion that bilingually exposed infants demonstrate fundamentally distinct patterns of attentional allocation compared with monolingually exposed infants, disengaging more readily from familiar stimuli and orienting preferentially to novel stimuli. An even more recent investigation suggests that bilingually exposed infants may engage more rapidly specifically to socially relevant stimuli (Mousley et al., 2023). The study also demonstrated increased attentional switching between paired stimuli.

Increased Variability and Higher-Order Generalization

As noted, an increased orientation toward variability in the environment—expressed as an attenuated preference for recurring information and enhanced preference for novel information—may facilitate categorization of information and promote generalization of existing knowledge to novel settings. Several studies have demonstrated that bilingually exposed infants exhibit greater generalization in how they categorize visual targets (e.g., Brito & Barr, 2012). These studies were conducted using a deferred imitation paradigm. The paradigm presents infants with an experimenter performing a target action on a puppet, namely removing a mitten. After a delay, infants' memories for the target action are measured. In general, infants are not able to retrieve the target action when the features of the object change (e.g., when the puppet changes from a gray mouse to a pink rabbit), suggesting that their memory of the action sequences is initially bound to the specific features of the object. Brito and Barr (2012) tested 18-month-old monolingual and bilingual infants in the United States originating from varying language backgrounds on this task. Language groups were matched on parental education and a composite index of SES. The authors found that after a 30-min delay, only bilingually exposed infants could generalize learned actions to novel exemplars (e.g., from a yellow duck to a black-and-white cow).

Brito and Barr (2014) extended this work to 6-month-old monolingual and bilingual infants in the United States originating from mixed language backgrounds. Groups were matched on socioeconomic factors. Researchers manipulated the number of visual features changed between the initial presentation of an action sequence and the deferred imitation prompt. The authors reported that both groups of infants were able to generalize to a single-feature change (e.g., a change in only the color of the puppet), but only bilingually exposed infants were able to generalize across two features (e.g., a change in both the color and shape of the puppet). That is, bilingually exposed infants could apply the same target actions to perceptually different agents.

In subsequent replications of this effect, the authors found that increased memory flexibility was present no matter whether bilingually exposed infants learned two distinct versus two similar languages (Brito et al., 2015) nor was there a greater advantage for those learning three (vs. two) languages (Brito et al., 2015; see also Brito et al., 2014). Moreover, increased memory flexibility in bilingually exposed infants was not influenced by the presence of a label to describe the action, suggesting that the underlying basis of the effect is generalization over task-irrelevant visual perceptual features (Barr et al., 2020).

In combination, the studies of Brito, Barr, and colleagues suggest that bilingually exposed infants generalize across visual targets more readily. Early in infancy, bilingually exposed infants may be better able to integrate multiple perceptual cues and to abstract key functional features from varied input. We note that visual generalization in bilingual learners is likely not the product of reduced sensitivity to visual difference. Prior studies have demonstrated increased sensitivity to visual difference in bilingual infants (D'Souza et al., 2021; Singh et al., 2015). Instead, these findings may reflect increased recognition that variations in visual features were nondiagnostic and task irrelevant. Although the studies reported do not establish causal pathways between the constructs measured, it is possible that greater flexibility in memory processing arises from a more variable environment that promotes broader exploration and facilitates abstraction of relevant cues (Hayne & Barr, 2022). That is, bilinguals may exhibit greater memory generalization (see Figure 1).

In addition to generalization across visual targets, there is empirical evidence that bilingually exposed infants may generalize across social agents more readily. For example, Singh, Tan, et al. (2020) demonstrated that in a language comprehension task, bilingual learners generalized across speakers' race, responding similarly to agents who were the same or a different race relative to the participant. In contrast, monolingual infants' responses to social agents depended on their race. It is possible that bilingual learners, on account of encountering increased variability, maintain looser associations between social agents and expected behaviors, resulting in more flexible and less constrained expectations of social agents. In further studies, researchers have investigated whether bilingual learners attach less valence to social agents by investigating racial bias in bilingual and monolingual learners. Two studies have demonstrated that bilingual infants (Singh et al., 2019) and preschool children (Singh, Quinn, et al., 2020) exhibited reduced other-race bias compared with monolingual peers. In these studies, bilingual children were less likely to interpret race information as positive or negative either in terms of their own liking (Singh, Quinn, et al., 2020) or in terms of viewing others as reliable informants (Singh et al., 2019). That is, bilinguals exhibit reduced social bias (see Figure 1).

Collectively, the studies reviewed in this section suggest that bilingual experience may lay a different attentional foundation for early learners. In particular, the increased complexity and variability of bilingual environments may stimulate attentional systems to survey a greater diversity of information within the environment. This may be reflected in an increased tendency to disengage from information as it becomes familiar (i.e., reduced familiarity preference) and to attend to information that is novel (i.e., increased novelty preference). Broader sampling of the environment may facilitate the uptake and abstraction of relevant cues as has been demonstrated in infants, children, and adults confronted with increased variability across a range of tasks and domains (Raviv et al., 2022). This in turn may result in robust categorization of information based on relevant cues that disregards nondiagnostic variation. The existence of robust categories could then promote generalization across different contexts.

As noted by theoretical accounts of beneficial effects of increased variability (e.g., Raviv et al., 2022), there may be tradeoffs to broad sampling. In particular, broad sampling may come at the cost, even if temporary, to specialization. Bilingual learners, like monolingual learners, must specialize in native linguistic systems. It is possible that bilingual learners, on account of distributed attention and learning and less focused attention, show a reduced native language specialization. In the next section, we discuss a final adaptation to bilingual environments, greater flexibility in perceptual processes, providing empirical evidence of potential tradeoffs of broad sampling.

Adaptation III: Openness to Perceptual Difference

To effectively learn two languages, learners must attend to more forms of linguistic variation compared with those learning one language. Moreover, specific types of variation often differ across languages. Distinguishing and independently mastering two languages requires infants to negotiate areas of convergence (where languages agree) and areas of conflict (where languages have opposing rules). For example, the specific sounds used in each language may have different levels of functional relevance across languages. Languages like English distinguish sounds based on consonants and vowels. However, a large body of languages, such as Mandarin Chinese, distinguish languages based on consonants, vowels, and tones. The presence of tones in a language means that the same syllabic sequence, produced at different tones (corresponding to vocal pitch), can have a different meaning. To complicate matters, pitch shifts associated with lexical tones overlap with intonational categories in nontone languages. For example, Mandarin has a rising tone and a level tone. This tone contrast is present in English and corresponds to the pitch contrast between questions and statements. In Mandarin, pitch serves both intonational and lexical contrasts, and in this way, there is both convergence and conflict.

Bilingually exposed infants must accrue sufficient exposure to each language in their environment to resolve these conflicts (Bosch & Sebastián-Gallés, 2003; Garcia-Sierra et al., 2016) and successfully negotiate the relationship between the two languages, which is critical to becoming bilingually proficient. Empirical studies have investigated sensitivity to contrast in bilingual infants in the visual and linguistic domain, producing varying results. The notion that bilingually exposed infants may be more sensitive to visual contrast is consistent with a recent investigation with bilingual adults by D'Souza et al. (2021). The authors reported effects of the age at which participants received bilingual exposure: those who were exposed to their first and second language simultaneously or in short succession were better at detecting subtle visual changes compared with those who learned their first and second languages further apart. That is, early bilinguals showed heightened change detection ability (see Figure 1). While this study investigated sensitivity to static images, recent research has demonstrated heightened sensitivity to subtle perceptual contrast in the visual domain in bilingual infants when viewing dynamic events (Singh, Göksun, et al., 2023). In combination, these findings imply that the effects of linguistic diversity transfer across domains from language to vision.

Studies investigating sensitivity to perceptual contrast at the nexus of visual and language processing have revealed increased visual sensitivity to nonnative linguistic information in bilingual infants. For example, Sebastián-Gallés et al. (2012) reported that Spanish–Catalan bilingually exposed infants were able to distinguish when silent faces switched from speaking in French to English at a level comparable to French–English bilingually exposed infants, even though the visual cues that distinguish French and English differ from those that distinguish Spanish and Catalan. Thus, exposure to two native languages was associated with changes in the attentional system that extended beyond the specifics of the input languages (Sebastián-Gallés et al., 2012). Described by Sebastián-Gallés as heightened perceptual attentiveness, this process captures how sensitivity to contrast is strengthened in bilingually exposed infants without direct exposure to those distinctions. Changes in perceptual attentiveness offer a potential explanation for differences between monolinguals and bilinguals that requires additional empirical attention. Overall, this finding points to increased flexibility and plasticity in bilingual learners compared with monolingual learners.

Studies in infant speech perception support accounts of increased bilingual flexibility, providing further evidence of attentiveness beyond the input. In speech perception, all infants are born with a high degree of plasticity, irrespective of language background. This plasticity enables infants to adapt to whatever environment—including language environment—they find themselves in. For example, infants are born with the capacity to discriminate many of the phonetic distinctions used across the natural languages of the world (Singh, Rajendra, & Mazuka, 2022; Werker & Tees, 1984). As the infant brain specializes to its given language environment between 6 and 12 months of age, it becomes better at discriminating the phonetic contrasts in its own (native) language—but at the cost of discriminating nonnative contrasts (Kuhl et al., 2006). Perceptual narrowing reflects an experience-dependent process of functional specialization (Johnson, 2000; Pascalis et al., 2014). This refers to the notion that early in development, a particular cortical region may respond to a wide variety of stimuli (e.g., environmental sounds), but adapt over development by responding more selectively to a subset of the stimuli (e.g., the speech sounds to which it is regularly exposed). In other words, the infant brain is initially highly plastic in order to later respond to variation in experience (in this case, speech input). Its plasticity subsequently declines as neural circuitry specializes to process the most relevant environmental stimuli (Oakes, 2017).

If an infant is exposed to two or more languages, however, then their neural plasticity might decline at a slower rate than if it were exposed to just one language, which has been borne out by empirical studies. For instance, Mercure et al. (2020) used functional near-infrared spectroscopy (fNIRS) to record brain activity in response to native and nonnative speech stimuli in monolingual infants and two groups of bilingual infants, unimodal (infants exposed to two spoken languages) and bimodal (infants exposed to one spoken and one sign language) bilinguals between 4 and 8 months of age. While monolinguals showed the expected left-localized responses to native speech, bilingual infants' brain responses were more widely distributed across the left and right hemispheres.

Petitto et al. (2012) also used fNIRS to investigate the neural correlates of perceptual narrowing to native phonetic contrasts in 4- to 6-month-old and 10- to 12-month-old monolinguals and bilinguals. The infants were presented with native language sounds, nonnative language sounds, and nonlinguistic tones. No statistically significant difference in neural activation between native and nonnative language conditions was detected in the younger group (4–6 months), neither in the monolinguals nor bilinguals. However, the 10–12-month-old bilingually exposed infants had more similar activity levels for the native and nonnative phonetic contrasts than the monolingual infants, who showed greater neural activation (in the left inferior frontal cortex [IFC]) to their native language.

The neuroimaging findings align with behavioral data and suggest that the capacity to discriminate phonetic contrasts remains flexible in the bilingual infant brain at a time when the monolingual infant brain narrows (or specializes) to its native language phonetic contrasts (e.g., Kuhl et al., 2008). For example, behavioral studies have revealed that bilingual infants continue to discriminate nonnative contrasts when monolingual learners' abilities have already attenuated (Petitto et al., 2012; Singh et al., 2017). Moreover, the extended period of plasticity lasts well into toddlerhood for some sounds (Burnham et al., 2018; Estes & Hay, 2015; Singh & Tan, 2021). It also extends to very distal linguistic stimuli that do not correspond to learners' native language inventories. For example, English monolingual 18- to 20-month-olds were not sensitive to Ndebele click contrasts that they had never encountered, but English-Mandarin bilingual 18- to 20-month-olds were sensitive to the same contrasts, entirely unfamiliar to them (Singh, 2018). That is, bilingual infants show a longer duration to native specialization than monolinguals (see Figure 1).

To summarize, these studies point to increased sensitivity to perceptual contrast in the visual domain, suggesting heightened attention to subtle differences across stimuli (see Table 1 for a summary of studies). This may arise from the more distributed patterns of attention reported in the previous section. As noted above, the increased environmental variability and complexity of bilingual input may lead learners to attend to a broader range of stimuli. This could foster greater memory generalizability. However, one consequence of broad sampling may be increased flexibility and reduced specialization in native language learning in the early phases of linguistic uptake. This in turn may modify the timeline of linguistic specialization, keeping bilingual infants in a holding pattern for a longer period of time before they specialize to their native language(s). Studies that have examined bilingual infants' linguistic sensitivities at multiple time points have revealed that this gap is temporary and closes by 2 years of age (Singh & Tan, 2021). In the following, we turn to a discussion of neuroscientific evidence for the behavioral processes described above.

The Neuroscience of Bilingual Attention

If infants adapt to more complex language environments by processing information faster, engaging in broader exploration, and maintaining sensitivity to perceptual contrast, then we would expect to observe relevant experience-dependent changes to the neurocircuitry that enables these cognitive processes and behaviors. Specifically, we should find experience-dependent adjustments to myelination, neural reorganization, neural oscillatory activity, and neural plasticity. While we discuss neural correlates of specific adaptations in previous sections, here we discuss the neural basis of more fundamental variation in infant attention.

Myelination

Information processing depends not only on interactions between the infant and their environment, but also on interactions between different neural populations in the infant brain. These different brain regions communicate via the long-range axons of neurons. To increase transmission speed from one neural population to another, the long-range axons can be wrapped in a lipid-rich substance called myelin (Waxman, 1980). Neuroimaging studies have found that the thickening of myelin (myelination) correlates with learning, and cellular studies have found that myelination is modulated by neural activity, and thus by infant–environment interactions (Almeida & Lyons, 2017; Fields, 2015; McKenzie et al., 2014; Mount & Monje, 2017). Myelination therefore plays an important role in processing complex stimuli. Although no neuroimaging studies have compared the process of myelination in bilingual infants with monolingual infants, neuroimaging studies have found greater myelination in bilingual adults than in monolingual adults, especially in frontal areas (Olsen et al., 2015; Pliatsikas et al., 2015) as well as in the long-range tracts that connect distal brain regions within and between hemispheres (Della Rosa et al., 2013; Luk et al., 2011).

Neural Reorganization

Information processing depends not only on transmission speeds between neural populations, but also on how neurons are connected—both within and between regions. In the adult literature, whenever participants select an action based on uncertain sensory evidence and reward expectation, the caudate nucleus is engaged (Doi et al., 2020); whenever participants reorient their attention to a novel stimulus, the inferior parietal lobe (IPL) is engaged (Kiehl et al., 2005; Numssen et al., 2021; Shomstein, 2012); and whenever participants suppress potentially interfering information as they explore novel stimuli, parts of the prefrontal cortex (e.g., dorsolateral prefrontal cortex [DLPFC]) are engaged (Collette et al., 2005; Ridderinkhof et al., 2004). These three regions (caudate nucleus, IPL, DLPFC) form the core of what is known as the frontoparietal control network (Dosenbach et al., 2008; Hon et al., 2006) and are the structures most associated with early bilingual experience (excluding structures within the language network). Specifically, functional neuroimaging studies have found greater activation of the frontoparietal control network in early-exposed bilinguals (e.g., Dash et al., 2022; Kovelman et al., 2008). Structural neuroimaging studies have found increased grey matter density in areas within the network (e.g., Della Rosa et al., 2013; Li et al., 2014; Mechelli et al., 2004; Zou et al., 2012). Diffusion tensor imaging (DTI) studies have found greater structural connectivity (white

Table 1
Summary of Relevant Studies on Bilingual Attention

Author(s)	Task	Age group	Language exposure of participants	Location of testing	Key findings
Barr et al. (2020)	Deferred imitation (demonstration with one of two stimuli sets, with and without labels; one familiar stimuli set, and one set of perceptually different stimuli at test)	18 months	Monolingual: English; English–Spanish, English–Arabic, English–French–Spanish, English–German, English–Korean–Spanish, English–Portuguese (some monolingual participants had bilingual exposure, but to a lesser degree than bilingual participants). Bilingual: English–Spanish; English–Chinese, English–Portuguese, English–German, English–Korean, English–Polish, English–French, English–Ga, English–Arabic, Spanish–English, Chinese–English, Portuguese–English, German–English, Korean–English, Swedish–English	Washington, District of Columbia, United States	Bilingual infants succeeded in generalizing at test across perceptually different stimuli, regardless of whether stimuli were labeled, while monolingual infants failed to do so.
Brito and Barr (2012)	Deferred imitation (novel stimuli at test)	18 months	Monolingual: English, Spanish, Portuguese Bilingual: L1: English, Spanish, Hebrew L2: Spanish, Portuguese, Hebrew, German, Cantonese	Washington, District of Columbia, United States	Bilingual infants outperformed monolingual infants in generalizing at test. Percent exposure to L2 predicted memory generalization.
Brito and Barr (2014)	Deferred imitation (novel stimuli at test: either one or two perceptual features changed)	6 months	Monolingual: English Bilingual: L1: English, Spanish, Russian, German, Portuguese, Greek, French, Arabic L2: English, Spanish, Arabic, Hebrew, French, Mandarin, Hungarian	Washington, District of Columbia, United States	Both monolingual and bilingual infants can generalize at test when one perceptual feature is changed (color), but not across two changed features.
Brito et al. (2014)	Deferred imitation (tested with one set of familiar stimuli and one set of perceptually different stimuli). Parent–child interaction (joint picture-book reading). "Spin the Pots" working memory task.	24 months	Monolingual: English, English–Spanish, English–French, English–Thai (some monolingual participants had bilingual exposure, but to a lesser degree than bilingual participants). Bilingual: L1: English, Spanish, French L2: Spanish, English, German, Italian, Hebrew, Chinese, Portuguese Trilingual: L1: English, Spanish, Hebrew, Arabic, Farsi, French, Portuguese L2: Spanish, German, Portuguese, Turkish, French, English, German L3: English, Spanish, Hebrew, Farsi, Danish, French	Washington, District of Columbia, United States	Only bilingual infants were able to generalize at test across different perceptual features. There were no differences between language groups for other memory tasks.
Brito et al. (2014)	"Hide the Pots" working memory task. Deferred imitation (novel stimuli used at test)	18 months	Monolingual: Spanish, Catalan, English Bilingual: Spanish–Catalan, Spanish–English Trilingual: L1: Portuguese, Spanish, Hebrew, German, English, French, Catalan L2: Lithuanian, Arabic, Turkish, German, Danish, Portuguese, English, Welsh, Spanish, French, Italian L3: English, Spanish, Serer, French, Danish, Catalan	Barcelona, Spain; Washington, District of Columbia, United States	Only bilingual infants generalized at test. There were no differences between language groups in the working memory task.
D'Souza et al. (2020)	Switch task: Infants first learn to make anticipatory looks to one side of a screen; they must then, during postswitch trials, inhibit their learned response, and make anticipatory looks to the other side.	7–9 months	Monolingual: English Bilingual/multilingual: diverse range (specific languages not reported)	Cambridge, United Kingdom; London, United Kingdom	Both groups could inhibit their learned response and redirect their anticipatory looks. Neither group learned to use the fragmented cues. Bilingual infants disengaged attention faster than monolingual infants.

(*table continues*)

Table 1 (*continued*)

Author(s)	Task	Age group	Language exposure of participants	Location of testing	Key findings
	Representation: Infants learn to use fragmented cues to make anticipatory looks; they are then tested with similar but more fragmented cues. Gap overlap: Infants must disengage their attention from a central stimulus to shift attention to a peripheral stimulus. Visual memory: Two detailed visual stimuli are presented; the details of one gradually changes from trial to trial.				Bilingual infants switched attention between visual stimuli more frequently than monolingual infants. A relationship between disengaging attention and switching attention was observed in bilingual infants, but not in monolingual infants.
D'Souza et al. (2021)	Gap overlap: Participants must disengage their attention from a central stimulus to shift attention to a peripheral stimulus. Visual memory: Two detailed visual stimuli are presented; the details of one gradually changes from trial to trial.	Adults ($M =$ 24.20 years; $SD = 6.18$)	Monolingual: English Bilingual/multilingual: diverse range (specific languages not reported)	Cambridge, United Kingdom	Early bilinguals disengaged attention faster than late bilinguals. Early bilinguals did not switch attention more frequently than late bilinguals (but early bilinguals were better at detecting the change than late monolinguals, and bilinguals switched attention more frequently than monolinguals).
Kalashnikova et al. (2021)	Anticipatory looking paradigm (auditory and visual stimuli conditions)	7 months	Monolingual: Spanish, Basque Bilingual: Spanish–Basque	Basque Country, Spain	Neither language group made successful anticipatory looks during postswitch trials.
Kovács and Mehler (2009)	Anticipatory looking paradigm (Experiment 2: different cue structure in pre and postswitch. Auditory cues used in Experiments 1 and 2, visual cues used in Experiment 3)	7 months	Not specified	Not specified	Bilingual infants' perseveration behavior during postswitch phase decreased faster and made more correct anticipatory looks.
Sebastián-Gallés et al. (2012)	Visual habitation (habituated to silent video clip of speaker; different language used at test)	8 months	Monolingual: Spanish; Catalan Bilingual: Spanish–Catalan	Barcelona, Spain	Only bilingual infants discriminated between two nonnative languages as well as their bilingual peers (who were native to those languages).
Singh et al. (2015)	Visual habituation (single image habituation and visual paired comparison at test)	6 months	Monolingual: English, Mandarin, Malay, Tamil Bilingual: English–Chinese, English–Tamil/Hindi/Bengali, English–Malay	Singapore	Bilingual infants showed a steeper habituation function and a reliable novelty preference at test.
Singh, Göksun, et al. (2023)	Intermodal preferential looking (familiarized to single image, paired comparison at test)	14, 19, and 24 months	Monolingual: English Bilingual: English–Mandarin	Singapore	Between 14 and 19 months, bilingual infants showed increased sensitivity to ground path distinctions. At 24 months, bilingual infants' sensitivity declined and converged with that of monolingual infants.
Singh et al., (2023)	Preferential looking (familiarized to a single image, paired with various novel stimuli)	5–6 months, 8–9 months	Monolingual: Spanish, Basque, English, Mandarin Bilingual: Spanish–Basque, Basque–Spanish, English–Spanish, English–Mandarin, Mandarin–English, English–Tamil	Basque Country, Spain, Singapore	Bilingual infants showed stronger novelty preference and oriented to novelty earlier. Infants with higher second-language exposure showed stronger novelty preference in the first block, and decreased preference in the third block.
Singh et al. (2017)	Habituation (phoneme discrimination -familiarized to one syllable from native and nonnative language; race discrimination—familiarized to one own race face and other race face)	10–11.5 months	Monolingual: English Bilingual: English–Mandarin	Singapore	Both language groups discriminated native stimuli, but not nonnative faces. Only bilingual infants discriminated nonnative phonemes.

Note. L1 = first language; L2 = second language; L3 = third language.

matter) between the core regions of the network (e.g., Grady et al., 2015).

Although there has been some debate over whether the frontoparietal control network has yet to emerge by early infancy, recent functional Magnetic Resonance Imaging (fMRI) studies suggest that the control network (as well as the dorsal attention network) is functional, with a broadly adultlike structure, from as early as 3 months of age (e.g., Ellis et al., 2021). The function of the control network is to direct information flow in the brain, and enable flexible, goal-directed cognition, working memory, inhibition, and task switching (Uddin et al., 2019). It does this partly by evaluating sensory input and acting through its preferential connections with the dorsal attention network, which in turn focuses and sustains visuospatial attention while suppressing distracting information.

A core part of the control network (the IPL) is also involved in the salience network. The salience network comprises the anterior IPL, right temporoparietal junction (a multimodal area at the edge of the IPL), and lateral prefrontal cortex. It constantly monitors the external world, and if an unexpected and potentially important stimulus is detected, acts as a circuit breaker—essentially deactivating the dorsal attention network as neural activation spreads across the salience network. The control network therefore supports broad exploration by integrating and coordinating the activity of other networks, and it develops differently as a function of early language experience.

Neural Oscillatory Activity

Neurocircuitry may also adapt to bilingual experience (and enable infants to rapidly shift attention and process information more efficiently) by increasing the brain's general state of "readiness." Brain readiness can be measured in different ways. One way is to measure alpha frequency band (∼8–12 Hz) power. Oscillatory activity typically reflects the synchronization of large ensembles of firing neurons (Buzsáki, 2006), but event-related oscillatory activity in the alpha frequency band can be either synchronized or desynchronized (Pfurtscheller & Lopes da Silva, 1999). The latter typically occurs during the preparation and execution of a movement. A recent study of undergraduates in Canada found more desynchronized alpha activity in bilinguals than monolinguals (Calvo et al., 2023). Although this study would need to be replicated in either bilingually exposed infants or bilingual adults who were exposed to their second language from an early age, the finding suggests that the bilingual brain may be more "ready" for action, an observation that would align with our hypothesis that bilingually exposed infants are more likely to rapidly disengage from familiar stimuli in order to shift attention toward novel stimuli (D'Souza & D'Souza, 2021; Singh, 2021).

Neural Plasticity

Neurocircuitry may also adapt to early bilingual experience by maintaining sensitivity to perceptual contrast. This would be achieved by retaining neural plasticity for a longer period. The timing and duration of early windows of plasticity involve interactions between basic biological processes (e.g., molecular pathways that modulate excitatory–inhibitory balance in neural circuits that utilize gamma-aminobutyric acid) and environmental input (see Hensch, 2004). As neural circuits self-organize (specialize) in response to specific input (e.g., a specific language), they stabilize via a complex cascade of interactions that include basic molecular and cellular structures, such as perineuronal nets that prevent synaptic pruning and outgrowth (Carulli et al., 2010; Miyata et al., 2012) and epigenetic modifications that downregulate genetic activity involved in synaptic rewiring (e.g., Maya Vetencourt et al., 2011; Putignano et al., 2007). However, if the neural circuitry is still actively self-organizing in response to more complex environmental stimuli (such as bilingual input), then the mechanisms that "close" (consolidate) circuitry will not be activated, and plasticity will be prolonged. We therefore predict more plasticity markers (e.g., protein synthesis) and fewer molecular and cellular structures that close plasticity (e.g., perineuronal nets) in infants exposed to greater environmental (language) complexity.

This modification to the timeline of specialization raises the question of whether bilingual flexibility trades off against the acquisition of native language knowledge. While behavioral studies suggest that bilingual and monolingual infants are similarly sensitive to native language contrasts (Mattock et al., 2010; Singh et al., 2017), neural evidence points to more subtle variation in the timing of native language specialization. In particular, bilingual infants have been shown to transition more gradually from processing speech at an acoustic level to processing speech at a linguistic level (see Ferjan Ramírez et al., 2017). This trend has been evidenced in two different types of neural analysis. The study by Petitto et al. (2012), described above, used fNIRS and reported that monolingual infants demonstrated increased involvement of the left IFC, a region that is involved in the detection of linguistic patterning, for native sounds relative to nonnative sounds. Bilingual infants demonstrated a more language-general response, reflected by similar activation levels in the IFC for native and nonnative sounds. Ferjan Ramírez et al. (2017) also reported a more gradual entry into native language sensitivity in bilingual infants using magnetoencephalography (MEG). This study additionally revealed that bilingual neural responses to speech contrasts extended to areas of the prefrontal and orbitofrontal cortex, areas not activated in monolingual infants. These areas are associated with language switching and language selection, suggesting that neurodevelopmental pathways to linguistic specialization may differ on account of early language experience. It remains an open question as to whether this early variation in native language specialization contributes to a slower rate of single-language uptake in bilingual learners (Hoff & Core, 2013).

Limitations

Neuroscientific evidence thus far suggests that bilingual experience leads to the reorganization of neural structures and processes. However, evidence of reorganization is not evidence of different cognitive abilities and direct evidence from early learners is needed to inform developmental theories. Performance may still be comparable across learners with different language backgrounds or it could vary in a task-dependent manner. It is therefore imperative for studies to link neural, cognitive, and behavioral data to better understand and explain infant adaptations to more complex environments. Failing to integrate data across methodologies will make it harder to interpret empirical findings within any single methodology (for more in depth discussion, see Karmiloff-Smith, 2010).

Summary

In sum, faster information processing, broader exploration, and prolonged sensitivity to perceptual contrasts may be enabled via experience-dependent adjustments to myelination, neural reorganization, neural oscillatory activity, and neural plasticity. Although more infant studies are required to test this hypothesis, the current evidence from adults suggests that bilingual experience is associated with greater myelination (processing speed), a strengthened fronto-parietal control network, increased "readiness," and more neural plasticity. Developmental theories that posit changes in myelination in response to bilingual experience require direct investigation at different stages of development.

Directions for Future Research

The evidence reviewed indicates that early bilingual experience has an early and profound impact on how infants explore and encode novel information in their environment. These cognitive adaptations in information gathering may lead to increased flexibility in visual perception, attentional orienting, language and social perception, and memory generalization and flexibility, which could be beneficial for bilingual learners. Specifically, they may assist bilingually exposed infants in negotiating reduced language input, greater variability, and increased sources of contrast. However, existing research leaves several questions unanswered which are critical to further our understanding of the impact that early exposure to high diversity in the environment has on infants' cognitive development. We discuss future directions in terms of methodological design, the nature of effects of bilingual experience on early attention and learning, and ancillary processes that may be influenced by bilingualism and environmental diversity more broadly. We address each issue in turn.

Methodological Approach

In various ways, broadening the range of methodological approaches used to examine effects of bilingualism on attention and learning would enrich the current narrative. It is noteworthy that previous studies have used cross-sectional designs within particular populations and have also largely focused on behavioral methods. As a result, the developmental trajectory of the neural and behavioral adaptations remains largely unknown and our knowledge of the relationship between behavioral change and neural development remains underdeveloped.

Longitudinal studies would inform us about the longer term consequences of an increased novelty orientation observed in bilingual infants. For example, prior studies have associated novelty preferences with increased curiosity and discovery-oriented exploration (Alberti & Witryol, 1994; Wentworth & Witryol, 2003). It remains to be seen whether an early novelty orientation diversifies exploratory behaviors later in development and whether individual variation in the tasks described above have long-term predictive validity.

Longitudinal studies would also inform us about how bilingual variation in attention links to other areas of reported bilingual variation. For example, attentional processing differences between monolinguals and bilinguals identified here may indeed turn out to be precursors to later differences in cognitive flexibility and switching that have long been reported between monolinguals and bilinguals. Cognitive flexibility is defined as the ability to adjust to changes in task demands and to switch between different rules and goals (Mahy & Munakata, 2015). Switching requires the ability to selectively attend, integrate, and adapt to multiple cues in the environment (Deák & Wiseheart, 2015). Bilingual language acquisition is associated with variation in cognitive flexibility and switching in infancy (Kovács & Mehler, 2009) and childhood (Adi-Japha et al., 2010; Bialystok & Martin, 2004; Bialystok & Senman, 2004; Carlson & Meltzoff, 2008), which continues throughout the lifespan (Bialystok et al., 2006; Costa et al., 2008). It is possible that perceptual and attentional processing differences may be key candidate precursors to emerging differences in cognitive flexibility via intermediate processes, such as memory flexibility. It is also possible that variation in early attentional patterns links to learning styles and the emergence of novelty-related behaviors, such as curiosity and creativity. This in turn may be linked to personality and social factors (for a discussion, see Ivancovsky et al., 2023). Lastly, longitudinal studies would be instrumental in determining causal pathways between bilingual exposure, behavioral derivatives, and neural adaptations.

Alternatively, there has been intense scrutiny of the robustness of differences in cognitive flexibility and switching between monolingual and bilingual learners (e.g., D'Souza et al., 2020; Kalashnikova et al., 2021; Paap et al., 2015) and whether factors associated with bilingual experience were adequately controlled for in past studies (van den Noort et al., 2019). Studies that have failed to find effects of bilingualism on cognitive flexibility have instead discovered evidence of novelty preferences, which are conflated with cognitive flexibility in paradigms where the reward for correct responding is presentation of a novel visual stimulus (Kalashnikova et al., 2021). Examining the role of attention in relation to cognitive flexibility would help to adjudicate on prevailing models of bilingual attention and cognition. In particular, longitudinal studies examining the trajectory of attentional processing, memory flexibility, and cognitive flexibility would help to trace developmental pathways and points of intersection. One approach to this issue would be to use multi-lab designs that directly compare bilingual performance across communities on the same construct (e.g., ManyBabies, n.d.; OSF ManyNumbers, n.d.; Q-BEx, n.d.). For instance, Dal Ben et al.' (2022) reanalysis of three open data sets investigating cognitive flexibility in infants revealed greater attentiveness to novel referents in bilingually exposed infants compared to monolinguals in three different linguistic communities.

Although multilab designs are often large and more diverse, their promise for understanding diversity resides in the extent to which these designs incorporate information about participant diversity. To date, there has not been a standard protocol for reporting participant diversity in developmental research, which may contribute to significant underreporting of participant demographic data (Singh, Cristia, et al., 2023). As a result of this underreporting, sample diversity—even across multilab studies—is often not well defined. One step in this direction is a recent ManyBabies initiative, ManyBabies Demographics, which provides developmental researchers with a standardized framework to capture participant demographic characteristics as a measure of different facets of sample diversity, including language experience (Singh et al., 2024). Greater recording of demographic information would allow for analysis of how infants' experiences influence the allocation of attention. In this vein, a recent large multilab study, ManyBabies 5, will examine both exogenous and endogenous modulators of infant attention in a large and diverse sample (Kosie et al., 2023).

In addition to longitudinal designs, diversifying the range of methodological tools would help to advance our understanding of underlying mechanisms that may drive variation in the processes described here. For example, the use of neuroimaging methods in addition to behavioral paradigms can elucidate the between-domain transfer of effects of bilingualism and the reach of environmental diversity. In recent years, advancements in neuroimaging have enabled researchers to investigate the neural foundations of cognition at increasingly younger ages. In particular, MEG and fNIRS can be safely used with young infants and allow for better localization of neural responses. Although there is neural evidence of attentional variation (i.e., language-related differences in how attention is allocated to visual stimuli) in children in relation to language experience (Barac et al., 2016; Chung-Fat-Yim et al., 2020; Mondt et al., 2009), young adults (Calvo & Bialystok, 2021; Calvo et al., 2023; Grundy et al., 2017; Pereira Soares et al., 2022), older adults (Dash et al., 2020), and even clinical populations (Baralt & Mahoney, 2020; Dash et al., 2021; Voits et al; 2020 for a review), research on infants is scarce (Arredondo et al., 2022). Studies using these methods indicate that bilingual infants may show reduced early native-language specialization in cortical regions responsible for language processing compared to their monolingual peers (e.g., Mercure et al., 2020; Petitto et al., 2012). Additionally, they may engage regions associated with dual language switching and language selection during speech processing tasks (Ferjan Ramírez et al., 2017). Further studies should examine the neural basis of attention in infants during their first few years of life and its connection to language selection, use, and processing.

The Nature of Effects of Bilingual Experience on Early Attention and Learning

It remains undetermined how much and what forms of environmental diversity are sufficient to reorient preferences to novelty. Whether novelty preferences emerge with threshold effects from a criterial amount of diversity remains an unexamined question, although prior studies have found links between the amount of bilingual experience and a novelty orientation (D'Souza et al., 2020; Singh et al., 2023). It is also not clear what degree of novelty infants prefer in more diverse environments. For example, Kinney and Kagan (1976) suggested that infants attend preferentially to stimuli that are "optimally discrepant" from their internalized representations. Empirical studies demonstrate that indeed infants prefer intermediate stimuli that lie between entirely predictable and highly surprising (C. Kidd et al., 2012, 2014). Whether this intermediate point—for the same set of stimuli—differs for monolingual and bilingually exposed infants on account of having internalized different sources of information is an important empirical question.

Future research should also strive to identify the precise aspects of early bilingual experience that lead to individual differences across linguistic and cognitive domains. While infants growing up in different bilingual families and communities may face the same challenge of acquiring two linguistic systems, their experiences with linguistic conflict, variability in the input, and diversity in the environment differ widely among individuals. The experience of an infant acquiring a minority heritage language from their caregivers at home and a majority language in a primarily monolingual community is unlikely to be comparable to the experience of an infant growing up in a bilingual community and hearing two languages used interchangeably. In this vein, we note the need to expand the investigative focus to less widely studied populations. Rocha-Hidalgo and Barr (2022) reported that the majority of studies conducted with infants in the bilingualism field included participants coming from nations such as the United States, Canada, and Spain. There was little to no representation from nations in South America, Africa, and Asia (all continents densely populated with multilingual communities), and a third of the studies failed to report their sample's geographic information.

Other factors that may determine variability in an infant's environment include the acoustic and linguistic distance between the languages, the language exposure strategy chosen by the caregivers, the degree to which the languages occur separately in the community, the child's relative exposure to each language, and caregivers' proficiency in the languages, among others. Researchers have widely debated how to assess early bilingual exposure during infancy and early childhood (Rocha-Hidalgo & Barr, 2022). Over time, more systematic and comprehensive approaches to measuring language exposure in the home have been developed, beginning with research by Sebastián-Gallés and colleagues (Bosch & Sebastián-Gallés, 2001), who developed the most widely used language exposure questionnaire (Rocha-Hidalgo & Barr, 2022). Recent technological and computational advances that allow for analyses of day-long recordings of infants' natural language environments can quantify many of these factors (Garcia-Sierra et al., 2016; Orena et al., 2019) and systematically assess how each source of variability relates to infants' behavior across development.

While bilingualism provides one example of how a learner's environment can become more diverse, there are myriad ways in which children's environments can become more complex. For example, at a physical level, the setup of one's home can introduce variation in sensory input with greater clutter increasing demands on sensory processing (Andeweg et al., 2021). At an individual and/or social level, racial or gender diversity can introduce a broader range of social categories in a learner's environment. In a recent example, the coronavirus disease pandemic may have increased complexity of the social visual environment by introducing a wider variety of ways in which speech is presented given variable use of face coverings (Bayet, 2022; DeBolt & Oakes, 2023; Singh & Quinn, 2023; Singh et al., 2021b). In this way, it is not clear to what extent effects of linguistic complexity are unique in their impact on behavior. It is possible that increased complexity, broadly construed, modulates exploratory behaviors introducing greater plasticity and additionally, that different forms of environmental complexity converge (or trade off) against each other to produce variation in exploration. Further research is essential to understanding interdependencies between different sources of environmental diversity.

Ancillary Developmental Processes Impacted by Bilingual Experience

Future research will benefit from targeting a wider range of cognitive domains to assess whether domain-general attentional mechanisms support domain-specific processing. For instance, because of increased uncertainty in bilingual environments, the use of visual information to learn new words differs in bilingual learners from monolingual learners (Barr et al., 2020; Kalashnikova et al., 2018; Rocha-Hidalgo et al., 2021; Singh et al., 2023). When learning new words, bilingual learners more readily generalize across variable cues (e.g., talkers; exemplars) compared with monolingual learners (Crespo et al., 2023) suggesting that pathways to word learning may differ in bilingual populations on account of variation in generalization.

There may also be broader memory systems that are impacted by greater distribution of attention. For example, older bilingual adults have been found to have better episodic memory than older monolingual adults (Schroeder & Marian, 2012). Episodic memory typically declines during the aging process. However, it is not clear how linguistic input interacts with the development of these systems during childhood. Early in development, memory processing becomes increasingly specific as young children accumulate enough repeated exposures to build a semantic knowledge base. By middle childhood, children's semantic knowledge base continues to grow and children become more precise and specific in their episodic memory processing perhaps due to increased pattern separation and completion (Ngo et al., 2019; Rollins & Cloude, 2018). It is possible that monolingual and bilingually exposed infants vary in the trajectory of the semantic memory knowledge base based on the trajectory of episodic memory development. A precise articulation of constructs and pathways linking bilingual experience and developmental processes relies on expanding the base of constructs tested and methods used based on hypothesized mechanisms.

Of the range of future directions suggested here, we suggest three primary areas of focus. First, convergence across tasks, measures, and methods to delineate underlying constructs more clearly is a key priority. Currently, different laboratories employ their own tasks and methods with little emphasis on multimethod approaches. Sharing of materials, code, and data and cross-laboratory replication initiatives would bring us closer to understanding the conditions under which bilingualism exerts effects on cognition. Second, as mentioned at the outset, bilingualism is one source of environmental diversity, often nested within other sources of diversity. Understanding how bilingualism, as a source of diversity, interacts with or trades off against other sources of diversity (e.g., interracial contact, culturally diversifying experiences) is a key priority in identifying whether bilingualism is unique in its developmental effects. Finally, a key question to emerge from recent research is the significance and impact of a novelty orientation. The broader consequences of bilingualism for aspects of later learning, such as the development of curiosity that may rely on a novelty orientation (C. Kidd & Hayden, 2015), remain interesting questions for further research. To this end, intersectional approaches that incorporate research from cognate fields (e.g., education, sociology, anthropology) may broaden the narrative around bilingual cognition.

Constraints on Generality: Effects of Selective Sampling, Methodological Choices, and Publication Bias

Research on bilingual cognition has been the subject of intense controversy (e.g., see Paap et al., 2015). Central to this controversy are sampling biases, methodological choices, and publication bias. In addition, there have been several instances of contradictory results in empirical findings which require careful attention to address. Examples include conflicting evidence for inhibitory control advantages in infancy (see Kovács & Mehler, 2009 vs. D'Souza et al., 2020; Kalashnikova et al., 2021), in childhood, and adulthood (see J. B. Morton & Harper, 2007). We treat each factor in turn.

First, regarding sampling, bilingualism research has tended to collapse across diverse samples to theorize broadly about bilinguals as a group. Bilingualism arises from a diversity of circumstances, which is reflected in the vast diversity of bilingual experiences. More careful reporting of the samples used in relation to the underlying population to which findings are generalized would lend greater precision to the study of bilingual cognition. Studies that more carefully match bilingual and monolingual learners along relevant variables (e.g., SES, vocabulary size, IQ, gender) are preferable to those that limit sample description to language experience and presume homogeneity across samples along other relevant dimensions (for a positive example, see Czapka et al., 2020). A clearer understanding of mediators, moderators, and careful invocation of causality would also improve the metascientific practices in bilingualism research (see Festman et al., 2023). This goal would also be assisted by a move toward open data, including demographic data, in a manner that allows for reuse and reanalysis. This is essential to addressing core issues of replicability and reproducibility in bilingualism research.

Second, methodologically, studies focused on bilingual cognition have opted for particular methods deemed to be suited to target constructs being queried. Little is known, however, about the suitability of these methods for diverse populations. Indeed, the uncritical transfer of methods from one setting to another presents a threat to multiple sources of validity. In future research, clear estimates of method variance (or invariance) (e.g., scalar, fractal, configural) of target measures are critical to evaluating how well suited these measures are to different bilingual populations. In general, these estimates are lacking in the field of bilingual cognition, making it complex to arrive at an integrative framework that generalizes across tasks and populations.

Finally, as with many areas of psychological research, publication opportunities favor studies that yield positive results. Bilingualism is no exception to this (see de Bruin et al., 2015). It is therefore possible that effects of bilingualism on varying domains of cognition exceed true effects due to the relative invisibility of null findings in the literature. Important disciplinary shifts, such as registered reports, will hopefully mitigate against some of this empirical bias.

Conclusion

This article has centered on the experience of bilinguals encountering multiple language streams as an example of how environmental diversity may affect the emergence of basic and overlapping cognitive processes such as attention, encoding, and generalization. Basic variation in these psychological processes may be responsive to increased environmental diversity and complexity, resulting in greater flexibility in attention, learning, and perception. The evidence suggests that relative to monolinguals, bilinguals may show different attentional tendencies inclusive of more rapid disengagement from familiar stimuli and engagement with novel stimuli. The more rapid disengagement from familiar stimuli may reflect more rapid encoding (i.e., initial learning of information) of such stimuli. Bilingual learners' abilities to readily move from familiar to novel stimuli may in turn facilitate broader sampling (exploration) of the environment and in turn may drive generalization across variation in input (i.e., extraction of invariance in the face of change). Of particular interest is that diversified language experience may drive similar changes in the visual and social domain as demonstrated, for example, by bilingually exposed infants showing greater memory generalization and less social bias. We note that further research is needed to confirm the existence of causal pathways between these processes. These findings suggest that diversity in environmental experience elicits changes in basic processes that are both domain specific and domain general, allowing for more adaptive responding to novel input encountered throughout the lifespan.

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