

Expertise, Ecosystem, and Emergentism: Dynamic Developmental Bilingualism

Hannah Claussenius-Kalman^a, Arturo E. Hernandez^a, and Ping Li^b

^aDepartment of Psychology, The University of Houston, 4800 Calhoun Rd, Houston, TX, 77004

^bDepartment of Chinese and Bilingual Studies, Faculty of Humanities, The Hong Kong Polytechnic University

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Correspondence concerning this article should be addressed to Hannah Claussenius-Kalman, Department of Psychology, University of Houston, 4800 Calhoun Rd, Houston, TX 77004. Email: hclausse@central.uh.edu

Abstract

Bilingual language representation and cognitive control effects may reflect the dynamic interactions among the complex learning environment, genotype of the individual, and developing cognitive abilities. In this paper we propose a framework considering such interactions. Specifically, we present a nonlinear, developmentally-oriented perspective in which each individual represents a developmental trajectory in multidimensional space. These trajectories focus on the cognitive ecosystem (and how said ecosystem changes over time) and individual expertise (which affects and is affected by the ecosystem). The interactions between ecosystem and expertise lead to the emergence of a system that is built to handle the communicative needs of the individual.

Key words: Neuroemergentism, language development, environment, expertise, second language acquisition, language diversity

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Researchers have established that bilingual experience shapes the brain in both function and structure (Costa & Sebastián-Gallés, 2014; Hernandez, 2013; Li, Legault, & Litcofsky, 2014)¹. The premise of this argument lies in the view that neural substrates are altered by the constant use of two or more languages as well as by the constant need to shift from one language to the other. However, the notion that bilingual language acquisition and cognitive control effects may reflect genotype-environment interaction has received much less attention in the literature; in fact, the very notion of neurocognitive effects does not take into account the interaction between the genotype and the environment. Whereas this approach is convenient from an experimental or statistical point of view, it ignores the idea that each person represents a trajectory in a multidimensional space. That is, each person comes to the learning task with a different level of cognitive capacity and language aptitude (Li & Grant, 2016), which has a cascading effect across the span of language development. In this article, we seek to further flesh out this perspective on language acquisition by arguing for the notion that **emergentism** indicates the product of interaction between **expertise** and **ecosystem**.

Ecosystem refers to properties of the language and learning environment. Specifically, ecosystem encompasses properties in terms of different features of the target language, input types (e.g., multiple languages that may be intermingled), input frequency, environmental features, language distance/similarity, context of learning (e.g., classroom instruction or

¹ We hold on to the validity of this statement independent of whether there is bilingual cognitive advantage given the ongoing contentious debates on the existence of such advantage (Antoniou, 2019; Bialystok, 2020; Paap et al. 2015).

immersed social learning), and diversity of language uses (e.g., code-switching and language control habits). *Expertise* can be thought of as individual aptitude that the learner brings to the task. This entails each learner's characteristics that are encompassed by variables such as age and individual differences in attentional capacity, working memory, cognitive control, and cognitive flexibility. *Emergentism* indicates the product of interaction between ecosystem and expertise: because of the specific expertise and ecosystem concerned, the emergent outcome or output of bilingual representation and processing will be different for each individual. Emergentism is a “non-linear dynamical process in which a process emerges from the combination of simpler parts into a more complex cognitive process” (Hernandez et al., p. 217). As formulated in various theoretical frameworks (e.g., Bates, 1999; Hernandez et al., 2005; Hernandez et al, 2019; Johnson, 2011; MacWhinney & O’Grady, 2015), emergentism suggests that specialization that occurs across development is caused by competition between brain regions, where some brain regions have initial biases that drive the interaction toward a particular type of expertise in the form of specialization.

Early exposure to a second language alters neural organization rapidly

It has been well-established that the brain copes with the need to maintain and switch between multiple languages by engaging cognitive control networks (Green, 1998; Abutalebi & Green, 2008). Hernandez (2013) proposes that “two languages live inside one brain almost as two species live in an ecosystem. For the most part they peacefully coexist and often share resources. But they also compete for resources especially when under stress, as occurs when there is brain damage” (p. 12). An abundant set of literature has demonstrated the neural processes involved in bilingual language processing in adults, and there is evidence that exposure

to a second language alters neural organization rapidly. The Dynamic Restructuring Model (DRM; Pliatsikas, 2020) integrates L2 acquisition demands on the brain with trajectories of structural adaptations by drawing upon components from previous models, including Bilingual Anterior to Posterior Subcortical Shift (BAPSS; Grundy, Anderson, & Bialystok, 2017) and the adaptive control hypothesis (Abutalebi & Green, 2016). This model proposes that two main components of initial L2 acquisition - the rapid learning of vocabulary and skills needed to control between lexical alternatives – result in structural increases in parietal and temporal regions implicated in language, as well as parts of the executive control network (including the inferior/middle frontal gyri and anterior cingulate cortex). Following initial learning, a consolidation stage occurs in which these same regions shrink back down due to synaptic pruning as language expertise increases. Conjectures can be made about a final “peak efficiency stage”, which is hypothesized to be a continuation of the consolidation stage (according to Pliatsikas more research needs to be done), but for the purposes of the present paper we focus on the dynamic processes related to initial L2 acquisition.

One example of how foreign language learners show clear adaptations to a second language even at the earliest stages of learning comes from a study that tracked participants in an introductory French course across a 9-month learning period (McLaughlin, Osterhout, & Kim, 2004). Participants were asked to complete a lexical decision task for French words and French pseudowords. It was found that after just 14 hours of total instruction time, participants in the “learner” group had a significantly larger N400 wave (which is known to be sensitive to semantic-conceptual integration) in response to French pseudowords than participants in the control group. This effect became larger as instruction time increased, and the researchers showed that at the final testing session, learners’ event-related potential (ERP) responses were

qualitatively similar to responses in the participants' native language. These results demonstrate how neural activity can develop sensitivity to linguistic judgments quickly, even before behavioral changes take place.

Other studies demonstrate how the early stages of L2 acquisition affect cortical structure. For instance, one study used magnetic resonance imaging (MRI) to examine cortical thickness of young adults in a military intensive interpreting training program before and after a 3-month period (Mårtensson et al., 2012). It was found that, relative to controls, participants in the language training program showed increases in cortical thickness in the left middle frontal gyrus (MFG), inferior frontal gyrus (IFG), and superior temporal gyrus (STG), areas which are critically important in both cognitive and linguistic processing. Additionally, they found an increase in the volume of the hippocampus, which plays a key role in vocabulary acquisition. These results are particularly important to the discussion of how bilingualism alters the brain because the structural brain changes occurred in a relatively short period in comparison to individuals who have learned L2 for an extended period. The results could be taken to mean that the IFG, MFG, STG, and hippocampus are a few structures that are more amenable to changes at the early phases of L2 learning.

Relevant to this point is the literature on bilingual-related neural adaptations in infants. Whereas the adult monolingual perceptual system is tuned to phonemes from that individual's native language, infants younger than 9 months are able to distinguish between phonemes of any language (Petitto et al., 2012; see also Eimas et al., 1971 for categorical perception in infants). In a study of 61 infants (half bilingual and half monolingual), Petitto and colleagues found that both bilingual and monolingual infants processed phonetic stimuli via neural regions that are implicated in language perception in adults (the left STG and IFG). However, the developmental

trajectory highlights a significant aspect of the study for our discussion: the neural responses in these regions differed between bilingual and monolingual infants across time. Although all infants showed more left STG activation to linguistic stimuli relative to musical tones, younger (9-month) infants also showed IFG activation during the perception of both native and non-native sounds; for older (12-month) infants, only the bilinguals showed this IFG pattern, whereas the monolingual infants showed left IFG activation only in response to native sounds (and not non-native sounds). This finding suggests that while the monolingual brain begins to tune itself to the sounds that are specific to the native language between 9-to-12 months, the bilingual brain continues to remain receptive to sounds from any language (see also Werker & Tees, 1984) and likely does so using the left IFG.

While our discussion above has focused on individual regions of interest in the brain, recent studies have begun to highlight the change or development of neural circuits or connectivity patterns as a result of L2 learning with regard to neural organization or reorganization (see Li & Grant, 2016; Pliatsikas, 2020). For example, Yang, Gates, Molenaar, and Li (2015) and Yang and Li (2019) showed that lexical tone learning can lead to significant differences in functional connectivity before and after learning/training. Such differences may be modulated by a variety of factors, including learner and environmental variables to be discussed below. Further, functional differences are often mirrored in structural brain reorganizations, as reviewed by Li et al. (2014; 3.1-3.4), Pliatsikas (2020), and Stein et al. (2014). For example, Stein et al. (2014) suggested that L2 learning in a naturalistic context (as opposed to classroom setting) might lead to enhanced white matter integrity in inferior fronto-occipital fascicle (IFOF) and superior longitudinal fasciculus (SLF), while Garcia-Penton et al. (2014) showed two important subnetworks that had higher interconnectedness in bilinguals than in monolinguals. It

remains unclear how L2 brain networks develop and change over time, and how such changes may manifest themselves differently in different individuals as a function of age, intensity of input, and cognitive ability of the individual before and after the learning experience.

Environmental variables impact second language acquisition: The bilingual ecosystem

Given our focus on the bilingual ecosystem, we want to highlight the impacts that the environment has on language acquisition. Environmental variables are those that are out of the bilingual individual's personal control, referring to factors such as age of L2 acquisition (AoA), language exposure, or the need to switch languages due to changes in the living environments. For example, early or late language acquisition can be determined by immigration, schooling, or a parent who chooses to speak either a home language or a societally non-dominant language. L2 AoA has been consistently shown to be a strong predictor of one's L2 attainment and proficiency (Birdsong, 2018). Earlier studies following the tradition of Critical Period Hypothesis tended to highlight AoA as a key variable for brain activity patterns (Kim et al., 1997; Weber-Fox & Neville, 2007), but later studies with fMRI/PET found that proficiency was more important (e.g., see Abutalebi et al., 2005 for review). However, various studies continued to point out the important role of AoA (e.g., Klein et al., 2014; Luo et al., 2019), and researchers have also been interested in disentangling the independent contributions of AoA and L2 proficiency (e.g., Nichols & Joanisse, 2016; see also Hernandez & Li, 2007). More recent work also has shown that bilinguals vary considerably in terms of cortical structure depending on AoA. Specifically, late bilinguals demonstrate structural changes to areas involved in cognitive control and language processing relative to early bilinguals. Claussenius-Kalman et al. (2019) showed that late

bilinguals had greater gray matter density in areas involved in language planning (including the bilateral MFG, IFG, right SMG, and left SFG) as compared to early bilinguals. Late bilinguals also had greater cortical thickness in regions implicated in top-down attentional control (left SPL), prelexical speech (left STG), and integration between auditory perception and motor production (left IPL). The authors postulated that when AoA is later, the brain utilizes different mechanisms (especially those that facilitate metacognitive processes) in order to achieve L2 acquisition and defend against L1 intrusions.

The findings from Claussenius-Kalman et al.'s study are particularly interesting for our current discussion, as the debate around the bilingual cognitive advantage has evolved into an examination of what is special about the bilingual's language experience. Specifically, the environment of the bilingual person is different from that of the monolingual, in the way in which bilinguals use two languages with different people (e.g., parents vs. co-workers), for different purposes (e.g., daily vs. academic communication), and in different contexts (e.g., family vs. workplace), which has previously been discussed as the Complementarity Principle (Grosjean, 2013). Given the (sometimes drastically) different environments in which the two languages are used, researchers are beginning to look at the impacts that the specific bilingual language experiences on the learning and representation of each language (see Li & Dong, 2020 for a review). This perspective led some investigators to propose the 'bilingualism on a spectrum' view in contrast to the view of bilingualism as a unitary or categorical variable. For example, DeLuca et al. (2019) recently investigated the combined neural correlates (brain structure and functional connectivity) of the effects of experience-based factors in bilingual language use, with experience measured as everyday usage of a language in different types of immersive settings. They found that brain plasticity is correlated with such factors and their

combined effects. DeLuca et al. (2020) further found that differences in the *duration* of bilingual experience and the *extent* of active language use predicted activation patterns in distinct brain regions, indicating distinct neural recruitments based on diverse bilingual experiences.

Timing, duration, and extent are the three key factors that Li et al. (2014) suggested bilingual researchers should investigate with regard to neuroplasticity, following the pioneering work of Bates (1999) on language development and neuroplasticity. The new empirical studies of DeLuca et al. (2019; 2020) are consistent with this view on focusing on the properties of the bilingual ecosystem, the specific language experiences of the language learner or user. To capture the ecosystem properties and the complexity and diversity of language experiences accurately, researchers have also provided several tools and measures (e.g., Gullifer and Titone, 2019; Li et al., 2019; Anderson et al., 2018). For example, Gullifer and Titone (2019) defined language entropy as a measure of the relative balance of the use of each language that is calculated from usage in five domains: home, work, social, reading, and speaking. Li et al. (2019) provided items in their language history questionnaire (LHQ3) to assess the bilingual individual's usage habits, purpose, and cultural identification for using each language (e.g., expressing emotions, remembering numbers, friends' language use percentages). The authors further suggest that the language entropy measure can be extended to a Multiple Language Diversity (MLD) measure (https://blclab.org/wp-content/uploads/2019/10/MLD_Score_191019.pdf). Such approaches to link the bilingual ecosystem with learning and processing also reflect recent efforts in a broader context to relate L2 acquisition with socio-cultural factors and social-affective processes (e.g., Bethel et al., 2020; Li & Jeong, 2020; MacWhinney, 2017).

In the case of the adult L2 learner, the difficulties associated with L2 learning ability are often credited to developmental factors (i.e. less plasticity in adulthood makes it harder to learn),

but it is equally important to point out that the adult learner's environment does not mimic that of the infant, for example, they do not get to learn to speak by babbling. To be specific, even if they take lessons, classes, or have an immersive experience in a new country, adults do not receive the consistent immersive and face-to-face interaction that infants receive from parents and other caretakers. For example, they do not receive 'contingent responses' from conversational partners as children do from adults/caregivers, while contingent response is a key factor underlying the positive correlation between child-parent joint attention to the learning environment and consequently, the child's sustained attention (Chen & Smith, 2016). It is important to note that in child L1 learning, face-to-face interaction involves a reciprocal affective relation: the child pays more attention to the object that the adult focuses on, the adult also provides a contingent response to the child's attention, which in turn increases the child's attention (i.e., leading to sustained attention; see Chen & Smith's 2016 experiment). Adult L2 learning often lacks such contingent responses and reciprocal interactions. Indeed, this problem is exacerbated by the Covid-19 pandemic under which students conduct online learning, where sustained attention to the learning content is difficult to maintain when there is a lack of reciprocal social interactions.

MacWhinney (2012) points out that as individuals get older it becomes increasingly difficult to fully integrate with the L2 community due to L1 responsibilities. Furthermore, communities are often more readily supportive of L2 learners who are young, and many of these experiences that make for the best learning environments (e.g., with corrective feedback and even teasing) are not experienced by the older learner due to an increased importance on social status and avoiding errors. MacWhinney referred to this issue as a "social isolation" risk factor. More recently, Caldwell-Harris and MacWhinney (under revision) fleshed out these ideas with respect to the environmental differences in cognitive, social and emotional dimensions between

early and late L2 learners. The different social and emotional contexts between early and late L2 learners have traditionally not been taken seriously. A systematic understanding of these dimensions in making up the perfect language learning environment for the child (as opposed to the adult) will be highly significant for understanding adult L2 learning (see discussion in Li & Lan, 2021; sections 4.2-4.3). Li and Jeong (2020) highlighted that such differences, especially social interaction, could have significant implications for revealing the brain mechanisms as well as behavioral patterns in L2 learning. They provided a model that draws heavily on the role of right-hemisphere processing that involves the supramarginal gyrus, the inferior frontal gyrus, and the basal ganglia for social L2 learning.

Taken together, these results support the view that different ecosystems that include language environment and specific language experiences will lead to different changes in the structure and function of the brain. Moreover, bilingualism is best characterized as a range of experiences, not a categorical phenomenon. More research is beginning to cast doubt on the tradition of simply contrasting bilingualism with monolingualism and to focus on the complexity and diversity of language experiences and the environments of the bilingual individuals. However, there is still much work to be done to understand the relationship between language representation in the brain (the emergent result developed) and the language experiences of the individual (the ecosystem for the learning).

Expertise and ecosystem: Individual abilities interact with their environment

There is considerable variability in proficiency even across individuals with similar language experience. Individual differences in cognitive abilities - executive function, working memory, and cognitive flexibility – have been related to L2 outcomes. In terms of working

memory, Wen, Biedrón, and Skehan (2017) argue that the central executive and phonological short-term memory (in line with Baddeley's (2003) model of working memory) have distinguishable influences on L2 acquisition, thereby affecting language proficiency and processing. Baddeley's (2003) model proposes that working memory is a limited capacity system with three components: a phonological loop, visuospatial sketchpad, and an episodic buffer. These components are driven by a central executive that directs attention to achieve cognitive tasks. The episodic buffer helps bind information between systems and between long-term memory and conscious awareness. Wen and colleagues (2017) argue that these distinct components of working memory can impact different aspects of language ability, such as phonetic coding ability, grammar sensitivity, and inductive language learning.

Other researchers have found that phonetic ability correlates with working memory (and musicality) but not cognitive control (i.e., Simon task), non-verbal IQ, verbal IQ, or reading speed (Reiterer, 2019). Phonological short-term memory has also been related to vocabulary and syntax acquisition in many studies in the last three decades (Gathercole & Baddeley, 1993; Ellis 2012; Martin & Ellis 2012).

There has also been a significant amount of interest in understanding the neural correlates of working memory and executive function with regard to cognitive behavior in general and language learning in particular (see Uddin, 2021 for a recent review). For example, Yang et al. (2015) found that executive function (inhibition) is an important predictor of L2 learning success and the underlying brain network could be identified even before learning takes place. A meta-analysis of 42 studies found that verbal working memory (the ability to hold and manipulate verbal data for a short duration) is localized to a network involving the basal ganglia, right cerebellum, and bilateral frontal and left parietal regions (Emch, von Bastian, & Koch, 2019).

This finding indicates that language-based processing is not completely left-lateralized (as some models propose) and instead draws upon right hemisphere areas to maintain and manipulate verbal data. A meta-analysis of verbal and non-verbal working memory (Rottschy et al., 2012) found working memory performance to be associated with a widespread fronto-parietal network. Rottschy and colleagues compared the neural correlates of verbal and non-verbal working memory tasks and found that verbal tasks showed more consistent activation in left Broca's area. However, non-verbal tasks demonstrated more consistent activation of dorsal/medial premotor regions.

As for executive control, this function has been related to more complex processes such as L2 comprehension, production, and interaction (Miyake & Friedman 1998; Skehan 2015). Executive control may have a more substantial impact than working memory on L2 acquisition. A meta-analysis (Linck et al., 2014) found greater effect sizes for the relationship between L2 proficiency outcomes and executive control than the relationship between L2 proficiency outcomes and the storage component of working memory. In terms of age-related effects, it has been argued (Wen et al., 2017) that phonological working memory is more important for younger L2 learners (especially for grammar development; French & O'Brien, 2008), whereas executive control is more important for later L2 learners who are near the end of development (i.e., university students; Doughty et al., 2010). Reiterer (2019) notes that the massive amount of language exposure in early infancy and childhood overrides the effects that genetic differences would otherwise have on L1 acquisition (this effect is also in part due to high neuroplasticity, see Hernandez & Li, 2007). The impact of individual differences is more apparent in the L2 because the L2 is often acquired later in development than the L1.

Cognitive flexibility seems to affect how individuals interact with their environment (Claussenius-Kalman & Hernandez, 2019; see Uddin, 2021 for a review of cognitive flexibility). Individuals who have high cognitive flexibility (which is influenced by genetic factors that affect dopamine availability; Vaughn et al., 2016) may choose to immerse themselves in a dense code-switching context (as defined by Green & Abutalebi, 2013). When speaking to two or more groups of monolinguals, a bilingual must switch between languages in order to communicate effectively. Abutalebi and Green associate this skill (“opportunistic planning”) with the left inferior frontal and right cerebellar circuit. Therefore, the continual decision to engage in environments that require flipping between languages would be made possible by higher engagement of these regions but is also likely to train and result in more efficient use of these regions. Work from Beatty-Martinez and colleagues (2019) provides evidence for this idea, with findings that the relationship bilinguals’ lexical access and cognitive control ability was explained by their interactional context. In other words, they found that engagement of cognitive control depended on environmental demands.

By the same token, bilinguals with lower switching ability may steer towards contexts that allow them to stay in one language, which Abutalebi and Green associate with skills such as goal maintenance and interference control. Although Abutalebi and Green’s model focuses on associations, and not causal relationships, between language experience and the brain regions that facilitate bilingualism, it is likely that more experience with particular skills would lead to practice effects and more efficient use of the brain regions involved in that skill. For bilinguals who prefer a single language context, this could result in more use of the left dorsal frontal cortex and parietal lobe. Research has tested these predictions and found that increased diversity in daily social language use relates to enhanced connectivity between the bilateral putamen and

anterior cingulate cortex (areas which are involved in context monitoring), as well as increased dependence on proactive (as opposed to reactive) control (Gullifer et al., 2018).

Dynamic developmental bilingualism: The bilingual individual and trajectory in a multidimensional developmental space

This discussion of interaction between an individual's ability and the ecosystem brings us to the central point of this paper, which is that each language learner represents a developmental trajectory in a multidimensional space that changes as time/learning progresses. MacWhinney (2006) describes how emergentism shows the interactions between long-term and short-term timescales. Timescales of language interactions can be organized into categories, with the slowest-moving including genetic and epigenetic categories, and the faster-moving including consolidation of new linguistic skills in the brain, and the fastest-moving including conversational processing (MacWhinney, 2015; 2019). In conversational processing, immediate contextual demands and interactions between speakers result in attentional demands and affect code-switching choices. Over time, these short-term interactions in turn have an effect on slower-moving processes, and vice versa. For example, faster-moving timescales of language use habits (e.g., contextual demands of when to code-switch and how often) interact with slower-moving processes over time (e.g., constant code-switching leads to consolidation of neural pathways that continue to promote similar code-switching habits).

The notion of neural reuse (Anderson, 2010) can provide additional insight into our discussion of timescale interactions. Whereas neural plasticity refers to brain adaptations that occur in response to new skill learning within a single lifespan, neural reuse proposes that evolutionarily older cortical structures can be repurposed for newer cognitive functions, such as

language. For example, given that reading is an evolutionarily newer skill, the part of the inferior temporal gyrus that becomes active during reading, the visual word form area (VWFA) cannot have evolved to specialize for this function. A more likely explanation is that this area is sensitive to detailed visual features, making it more easily lendable to orthographic recognition than other parts of the cortex (Hernandez et al., 2019). That said, language seems to lend itself to a wide set of cortical areas, including motor and spatial processing regions that become active as a form of conceptual representation (Anderson, 2010).

Interactive Specialization (Johnson, 2011) argues that communication between brain regions changes as a result of skill acquisition, and the nature of this change, which includes organization and re-organization, depends on previous experience and developmental stage. In this perspective, the brain recruits different neural connections across development in order to acquire and facilitate a skill. In terms of bilingualism, the competition model (Bates & MacWhinney, 1987; Hernandez, Li, & MacWhinney, 2005; MacWhinney, 2012) fits nicely with this idea, proposing that language systems are flexible and competitive. This model argues that language representation emerges “dynamically out of the interactions between the learning environment (features of the language to be learned) and the representation system (features of the learning brain), so that developmental trajectories can be clearly charted as a function of the interplay between experience and the underlying neural network” (Li, Legault, & Litcofsky, 2014, p. 318). It seems to be the case that high neuroplasticity in subcortical regions (such as those implicated in implicit learning) increases the sensitivity of the brain to learning multiple languages at a young age (see sensorimotor hypothesis, Hernandez & Li, 2007). The sensorimotor hypothesis provides an account for why early AoA is a strong predictor of language proficiency, especially in terms of native-sounding accent. That is, subcortical motor pathways

involved in speech production produce high plasticity early in development (Kuhl & Rivera-Gaxiola, 2008). Even in vocabulary, adult L2 learners show different neural networks in terms of the connection between the sensorimotor and language regions: in contrast to L1 lexical processing that engages a more integrated brain network connecting key language areas with areas of sensorimotor and semantic integration, L2 processing does not involve strong connections between the semantic integration hub and sensorimotor regions.

However, the framework we present here aims to explain additional factors of bilingual language outcomes beyond timing of language acquisition and to provide further insights into the emergent properties of the interaction between ecosystem and expertise. Yang and Li (2012) demonstrated how artificial language learning can recruit differential patterns of connectivity in brain regions depending on method of instruction. In their study, one group was taught to focus on the syllable sequences (explicit group) and another group was given simple exposure to the sequences (implicit group). Both groups activated similar regions, but explicit learning was related to the use of the insula as a mediator and implicit learning was related to a frontal-striatal network. This demonstrates how differential networks help facilitate foreign language learning. Ecosystem factors (such as method of instruction) can then go on to interact with expertise (e.g., cognitive abilities). In the same vein, if the context of learning is different (e.g., immersive learning vs. classroom-based learning), the learner's brain may tap into a different network in the left vs. right hemispheres (see Li & Jeong, 2020). In light of the Interaction Specialization model, results from experiments like the one conducted by Yang and Li would also differ depending on developmental stage. The sensorimotor hypothesis would suggest that the child brain would be more receptive to implicit learning than the adult brain (cf. Ullman's 2001, 2016 declarative/procedural model of language learning further discussed below).

Few studies have examined the emergent properties of bilingualism in terms of the interaction between the ecosystem and the genetic underpinnings of the learner. Reiterer (2019) points out that genetics have a stronger effect on L2 proficiency than L1 proficiency, positing that massive time exposure at an early age overrides genetic influences on L1 aptitude. For example, research with twins has found that second language achievement is composed roughly of a 50% heritable component. Of this 50%, one third has been found to share variance with general intelligence, a third with first language ability and a third is specific to L2 learning (Rimfield, Dale, & Plomin, 2015).

Despite the fact that there is still much work to be done to understand how genetic background influences second language acquisition, one recent study exemplified how such an interaction could also result in individual differences in language proficiency. Vaughn and Hernandez (2018) found a three-way interaction between genetic variants, age of L2 acquisition (AoA), and balanced language proficiency in adult Spanish-English bilinguals. Specifically, the genetic predictors of higher, more balanced proficiency varied across different times of AoA. In bilinguals with earlier AoA, higher, more balanced proficiency was predicted by A1 carrier status (a genetic variant of the dopamine receptor D2 (DRD2) gene); by contrast, in bilinguals with later AoA, higher, balanced proficiency was predicted by a different gene Val158Met (a genetic variant of the Catechol-O-methyltransferase gene, COMT). Whereas Val158Met carrier status is known to be related to mid-level cognitive flexibility compared to other variants of COMT, A1 carrier status is associated with the highest levels of cognitive flexibility compared to non-carrier status. However, this study did not examine the entire genome, so more work needs to be done to disentangle the cause-and-effect relationships among individual differences in cognition, L2 learning and attainment, and genetic variation,

Patterns arising from the ecosystem-learner interaction suggest that the emergent trajectory might look quite different across time, and it is thus important to consider genetic factors given that bilinguals in similar environments are known to vary in proficiency and ultimate attainment (Granena & Long, 2013). Based on the extant evidence, we also argue that whereas ecosystem plays a larger role early in language development due to a highly plastic brain that can readily adapt to a multilingual environment, expertise has a more substantial impact later in development (Hart & Risley, 1995; Reiterer, 2019; Rimfeld, Dale, & Plomin, 2015). This pattern fits with research showing that in general, early AoA is one of the strongest predictors of high proficiency whereas late AoA can lead to large variations in L2 learning ability.

Existing theories of language learning are also consistent with this view. Ullman (2016) notes that both L1 and L2 learning engages procedural memory and declarative memory, but procedural memory seems to be well-established early in life, whereas declarative memory is more readily available following early development. The adult L2 learner is more likely to make use of the declarative memory system in order to achieve L2 acquisition; however, this system processes information less rapidly and automatically than the procedural memory system. So although the largest gains in adult L2 acquisition occur most predictably in the presence of massive exposure and intensive training (such as that in immersion programs or intensive military training programs) (Mårtensson et al., 2012), these gains likely occur via brain mechanisms associated with declarative memory (Bradley et al., 2013) rather than procedural memory. Nevertheless, the boundary between early vs. late L2 AoA in this regard can be blurred if the learner is able to use strategies involving thinking in L2, social learning, and community integration, as such strategies could engage more procedural memory as child L2 learning does

(Caldwell-Harris & MacWhinney, under revision; Li & Jeong, 2020). In addition, recent work in digital language learning attempts to simulate the features or affordances in immersive social learning contexts and could help with providing enhanced bilingual ecosystems that are more comparable to early L1 ecosystems of learning (see discussion in Li & Lan, 2021).

Individual differences can also shed light on our understanding of hyperpolyglotism. Hyperpolyglots, and to a lesser extent, multilinguals, likely have a genetic predisposition towards language learning ability (Erard, 2012; Hyltenstam, 2016), but in order to foster this skill the individual would need to be raised in an environment that lends itself to learning multiple languages (Claussenius-Kalman & Hernandez, 2019). The ecosystem-learner interaction could result in increased multilingual aptitude and lead the individual to land in environments that are more conducive to this skill. Such interactions in the end will lead to further opportunities and experiences in language use for the individual. Although hyperpolyglotism is poorly understood (Erard, 2012), a case study showed that a hyperpolyglot had variable brain structure relative to 11 bilinguals and monolinguals, suggesting that language competence could be related to unique cytoarchitectonic structure in Broca's area (Amunts, Schleicher, & Zilles, 2004). The neural profile of hyperpolyglotism (and multilingualism) is likely a consequence of this interaction between genetics and practice effects (see Onnis, Truzzi, & Ma, 2018 for discussion of epigenetics).

Our overall proposition in this article contrasts with previous models that focus on the linear components of language ability across development, which unfortunately has led to splitting these learning components into innate versus environmental factors. Instead, we propose that the neural basis of bilingualism is emergent by nature. Ecosystems interact with expertise (the result of the interaction between environmental factors and individual abilities), causing the

language outcome for each individual to emerge differently in a multidimensional space across developmental time. This means that each L2 learner can be thought of as representing a trajectory in this multidimensional space. Expertise, ecosystem, and emergentism provide a framework within which we can better understand the multidimensional dynamic trajectories, and the relevant individual differences and developmental changes in L2 learning successes and failures.

Recommendations for future research

An advanced model of bilingualism should be falsifiable, account for individual differences, and be able to make predictions about future language outcomes. Although costly in the respects of time and funding, longitudinal research will help achieve this goal. Neural networks can also be used in tandem with longitudinal analysis to make and test predictions. The benefit of neural networks is that they can provide a platform to investigate the cognitive mechanisms that facilitate dual language proficiency and switching with the added benefit of being able to either control for variables such as socioeconomic status, context/amount of exposure, and age of acquisition.

We also need to abandon the static view of bilingualism as a categorical variable. A number of tools exist for quantifying bilingualism on a continuous spectrum, including the Multiple Language Diversity (MLD) measure (https://blclab.org/wp-content/uploads/2019/10/MLD_Score_191019.pdf), language history questionnaire 3 (LHQ3, Li et al., 2019), and balanced proficiency (as calculated in Vaughn & Hernandez, 2018). Individual aptitude should be measured carefully, and genetic information should be taken into account when possible. Further building on the point that we need to abandon the static view of bilingualism, we need to consider the typological distance between the first and second language,

given that bilinguals are more easily able to transfer L1 reading procedures to an L2 that is typologically similar to the L1 (Ben-Yehuda et al., 2019). At large, methods that examine the interactions between the learner and the environment, and do so at multiple points across development, will elucidate the multidimensional dynamic trajectory of language.

Controversies in the bilingual literature, for example the debate over the bilingual cognitive advantage (Bialystok, 2011; de Bruin, Treccani, & Della Sala, 2015; Paap & Sawi, 2014), may see new insights by taking an emergent perspective. That is, research that uses an emergent perspective can offer a more clear understanding of bilingualism not only by examining individual differences, but, whenever possible, examining interactions between individual differences and neural processing across time (Hernandez et al., 2019). For example, the adaptive control hypothesis posits that because language production and perception are governed by control processes, bilinguals make greater use of cognitive control mechanisms in order to use the target language. This results in adaptation of these cognitive control circuits to meet the language demands. However, although this model takes into account environmental differences (by grouping bilinguals into three interactional contexts), taking into account developmental processes and the role of individual aptitude can provide us with a more complete picture. Understanding the roles of expertise, ecosystem, and emergentism can help us continue to develop more precise and detailed models of the neural mechanisms underlying bilingualism.

References

- Abutalebi, J., Cappa, S. F., & Perani, D. (2005). What can functional neuroimaging tell us about the bilingual brain? Chapter in J. F. Kroll & A. M. B. De Groot (Eds.), *Handbook of Bilingualism: Psycholinguistic Approaches*. New York, NY: Oxford University Press.
- Abutalebi, J. & Green, D. (2008). Control mechanisms in bilingual language production: Neural evidence from language switching studies. *Language and Cognitive Processes, 23*(4), 557-582. doi:10.1080/01690960801920602
- Abutalebi, J. & D.W. Green. (2016). Neuroimaging of language control in bilinguals: Neural adaptation and reserve. *Bilingualism: Language and Cognition, 19*, 1–10.
- Amunts, K., Schleicher, A., and Zilles, K. (2004). Outstanding language competence and cytoarchitecture in Broca's speech region. *Brain and Language, 89*(2): 346–353. doi:10.1016/s0093- 934x(03)00360- 2.
- Anderson, M. L. (2010). Neural reuse: A fundamental organizational principle of the brain. *Behavioral and Brain Sciences, 33*, 245–266. <http://dx.doi.org/10.1017/S0140525X10000853> discussion 266-313.
- Anderson, J. A., Mak, L., Chahi, A. K., & Bialystok, E. (2018). The language and social background questionnaire: Assessing degree of bilingualism in a diverse population. *Behavior Research Methods, 50*(1), 250–263.
- Antoniou, M. (2019). The advantages of bilingualism debate. *Annual Review of Linguistics, 5*(1). doi:10.1146/annurev-linguistics-011718-011820
- Baddeley, A. (2003). Working memory: looking back and looking forward. *Nature Reviews Neuroscience, 4*, 829-839. <https://doi.org/10.1038/nrn1201>

- Bates, E. A. (1999). Plasticity, localization, and language development. In S. H. Broman, J. M. Fletcher, S. H. Broman, & J. M. Fletcher (Eds.), *The changing nervous system: Neurobehavioral consequences of early brain disorders*. (pp. 214-253). New York, NY, US: Oxford University Press.
- Bates, E., & MacWhinney, B. (1987). Competition, variation, and language learning. In B. MacWhinney (Ed.), *Mechanisms of language acquisition*. Hillsdale, NJ: Lawrence Erlbaum.
- Beatty-Martínez, A. L., Navarro-Torres, C. A., Dussias, P. E., Bajo, M. T., Guzzardo Tamargo, R. E., & Kroll, J. F. (2020). Interactional context mediates the consequences of bilingualism for language and cognition. *Journal of experimental psychology. Learning, memory, and cognition*, *46*(6), 1022–1047. <https://doi.org/10.1037/xlm0000770>
- Ben-Yehudah, G., Hirshorn, E. A., Simcox, T., Perfetti, C. A., Fiez, J. A. Chinese-English bilinguals transfer L1 lexical reading procedures and holistic orthographic coding to L2 English. *Journal of Neurolinguistics*, *50*, 136-148.
<https://doi.org/10.1016/j.jneuroling.2018.01.002>
- Bethel, A., Ward, C., & Fetvadjev, V. H. (2020). Cross-cultural transition and psychological adaptation of international students: The mediating role of host national connectedness. *Frontiers in Education*, *5*(539950), 1-12. doi: 10.3389/educ.2020.539950
- Bialystok, E. (2011). Reshaping the mind: The benefits of bilingualism. *Canadian Journal of Experimental Psychology*, *65*(4), 229-235.
- Bialystok, E. (2020). Null results in bilingualism research: What they tell us and what they don't. *Journal of Multilingual Theories and Practices*, *1*(1), 8–22.
<https://doi.org/10.1558/jmtp.17104>

- Birdsong, D. (2018). Plasticity, variability, and age in second language acquisition and bilingualism. *Frontiers in Psychology*, 9, 81. <https://doi.org/10.3389/fpsyg.2018.00081>
- Bradley, K. A., King, K. E., & Hernandez, A. E. (2013). Language experience differentiates prefrontal and subcortical activation of the cognitive control network in novel word learning. *Neuroimage*, 67, 101-110. doi:10.1016/j.neuroimage.2012.11.018
- Caldwell-Harris, C. & MacWhinney, B. (Under revision). Age Effects in Second Language Acquisition: Expanding the Emergentist Account. *Behavioral and Brain Sciences*.
- Claussenius-Kalman, H. & Hernandez, A. E. (2019). The Neurocognitive Effects of Multilingualism throughout the Lifespan. Chapter in J. W. Schwieter (Ed.), *The Handbook of the Neuroscience of Multilingualism*. Hoboken, NJ: Wiley-Blackwell.
- Costa, A. & Sebastián-Gallés, N. (2014). How does the bilingual experience sculpt the brain? *Nature Reviews Neuroscience*, 15, 336–345. <https://doi.org/10.1038/nrn3709>
- de Bruin, A., Treccani, B., & Della Sala, S. (2015). Cognitive advantage in bilingualism: An example of publication bias? *Psychological Science*, 26(1), 99–107. <http://dx.doi.org/10.1177/0956797614557866>.
- DeLuca, V., Rothman, J., Bialystok, E. & Pliatsikas, C. (2019). Redefining bilingualism as a spectrum of experiences that differentially affects brain structure and function. *PNAS*, 116(15), 7565-7574. <https://doi.org/10.1073/pnas.1811513116>
- DeLuca, V., Rothman, J., Bialystok, E., & Pliatsikas, C. (2020). Duration and extent of bilingual experience modulate neurocognitive outcomes. *NeuroImage*, 204. <https://doi.org/10.1016/j.neuroimage.2019.116222>
- Doughty, C. J., S. G. Campbell, M. A. Misyevy, M. F. Bunting, A. R. Bowles & J. T. Koeth (2010). Predicting near-native ability: The factor structure and reliability of Hi-LAB. In

- M. T. Prior, Y. Watanabe & S-K. Lee (eds.), Selected proceedings of the 2008 Second Language Research Forum. Somerville, MA: Cascadilla Proceedings Project. 10–31.
- Eimas, P. D., Siqueland, E. R., Jusczyk, P., & Vigorito, J. (1971). Speech perception in infants. *Science*, *171*, 303–306.
- Ellis, N. C. (2012). Formulaic language and second language acquisition: Zipf and the phrasal Teddy Bear. *Annual Review of Applied Linguistics*, *32*, 17–44.
- Emch, M., von Bastian, C. C., & Koch, K. (2019). Neural Correlates of Verbal Working Memory: An fMRI Meta-Analysis. *Frontiers in Human Neuroscience*, *13*(180) doi: 10.3389/fnhum.2019.00180
- Erard, M. (2012). *Babel No More: The Search for the World's Most Extraordinary Language Learners*. New York, NY: Free Press.
- French, L. M & I. O'Brien (2008). Phonological memory and children's second language grammar learning. *Applied Psycholinguistics* *29*, 463–487.
- Gathercole, S. E. & Baddeley, A. D. (1993). Phonological working memory: A critical building block for reading development and vocabulary acquisition? *European Journal of Psychology of Education*, *8*(259). <https://doi.org/10.1007/BF03174081>
- Granena, G. & Long, M.H. (2013). Age of onset, length of residence, language aptitude, and ultimate L2 attainment in three linguistic domains. *Second Language Research*, *29*(3): 311–343.
- Green, D. (1998). Mental control of the bilingual lexico-semantic system. *Bilingualism: Language and Cognition*, *1*(2), 67-81. doi:10.1017/S1366728998000133

- Green, D. W. & Abutalebi, J. (2013). Language control in bilinguals: The adaptive control hypothesis. *Journal of Cognitive Psychology*, 25(5), 515-530.
doi:10.1080/20445911.2013.796377
- Grey, S., Sanz, C., Morgan-Short, K., & Ullman, M. T. (2018). Bilingual and monolingual adults learning an additional language: ERPs reveal differences in syntactic processing. *Bilingualism: Language and Cognition*, 21(5), 970-994.
doi:10.1017/S1366728917000426
- Grosjean, F. (2013). Bilingualism: A short introduction. Chapter in F. Grosjean & P. Li (eds.), *The Psycholinguistics of Bilingualism*. West Sussex, UK: Wiley-Blackwell.
- Grundy, J.G., J.A.E. Anderson, & E. Bialystok. (2017). Neural correlates of cognitive processing in monolinguals and bilinguals. *Annals of the New York Academy of Sciences*, 1396, 183–201.
- Gullifer, J. W., Chai, X. J., Whitford, V., Pivneva, I., Baum, S., Klein, D., & Titone, D. (2018). Bilingual experience and resting-state brain connectivity: Impacts of L2 age of acquisition and social diversity of language use on control networks. *Neuropsychologia*, 117, 123-134. <https://doi.org/10.1016/j.neuropsychologia.2018.04.037>
- Gullifer, J.W. & D. Titone. 2019. Characterizing the social diversity of bilingualism using language entropy. *Bilingualism: Language and Cognition*, 23(2), 283–294.
<https://doi.org/10.1017/S1366728919000026>
- Hart, B., & Risley, T. (1995). Meaningful differences in the everyday experience of young American children. Baltimore, MD: Paul H. Brookes Publishing Co.
- Hernandez, A. E. (2013). *The bilingual brain*. Oxford university press. New York, NY.

- Hernandez, A. E., Claussenius-Kalman, H., Ronderos, J., Castilla-Earls, A., Sun, L., Weiss, S., & Young, D. (2019). Neuroemergentism: A Framework for Studying Cognition and the Brain. *The Journal of Neurolinguistics*, 49. doi:10.1016/j.jneuroling.2017.12.010
- Hernandez, A. E. & Li, P. (2007). Age of acquisition: its neural and computational mechanisms. *Psychological Bulletin* 133 (4): 638–650. doi:10.1037/0033-2909.133.4.638.
- Hernandez, A. E., Li, P., & MacWhinney, B. (2005). The emergence of competing modules in bilingualism. *Trends in Cognitive Sciences*, 9(5), 220-225.
<https://doi.org/10.1016/j.tics.2005.03.003>
- Horwitz, E. (2010). Foreign and second language anxiety. *Language Teaching*, 43(2), 154-167.
doi:10.1017/S026144480999036X
- Hyltenstam, K. (2014). Language awareness in polyglots. Paper presented at the 12th International Conferences Association for Language Awareness, Hamar, Norway.
- Johnson, M. H. 2011. Interactive specialization: a domain-general framework for human functional brain development? *Developmental Cognitive Neuroscience*, 1, 7-21.
- Kim, K. H. S., Relkin, N. R., Lee, K.-M., & Hirsch, J. (1997). Distinct cortical areas associated with native and second languages. *Nature*, 388, 171-174.
- Klein, D., Mok, K., Chen, J.K., and Watkins, K.E. (2014). Age of language learning shapes brain structure: a cortical thickness study of bilingual and monolingual individuals. *Brain & Language*, 131, 20–24. doi:10.1016/j.bandl.2013.05.014.
- Kuhl, P. & Rivera-Gaxiola, M. (2008). Neural Substrates of Language Acquisition. *Annual Review of Neuroscience*, 31, 511-534.
<https://doi.org/10.1146/annurev.neuro.30.051606.094321>

- Li, P., & Dong, Y. (2020). Language experience and cognitive control: A dynamic perspective. *Psychology of Learning and Motivation, 72*, 27-52. (Volume: *Adult and Second Language Learning*, eds., K.D. Federmeier & H.-W. Huang)
- Li, P., & Grant, A. (2016). Second language learning success revealed by brain networks. *Bilingualism: Language and Cognition, 19*(4), 657-664.
doi:10.1017/S1366728915000280
- Li, P., & Jeong, H. (2020). The social brain of language: Grounding second language learning in social interaction. *Npj Science of Learning, 1*-9. <https://doi.org/10.1038/s41539-020-0068-7>
- Li, P. & Lan, Y.-J. (2021). Digital Language Learning (DLL): Insights from Behavior, Cognition, and the Brain. *Bilingualism: Language and Cognition, 1*–18.
<https://doi.org/10.1017/S1366728921000353>
- Li, P., Legault, J., & Litcofsky, K.A. (2014). Neuroplasticity as a function of second language learning: Anatomical changes in the human brain. *Cortex, 58*, 301-324. doi: 10.1016/j.cortex.2014.05.001
- Linck, J. A., P. Osthus, J. T. Koeth & M. F. Bunting (2014). Working memory and second language comprehension and production: A meta-analysis. *Psychonomic Bulletin & Review 21.4*, 861–883.
- Luo, D., Kwok, V. P. Y., Liu, Q., Li, W., Yang, Y., Zhou, K., [...] & Tan, L. H. (2019). Microstructural plasticity in the bilingual brain. *Brain and Language, 196*.
<https://doi.org/10.1016/j.bandl.2019.104654>
- MacWhinney, B. (2006). Emergentism – Use often and with care. *Applied Linguistics, 27*(4), 729-740. doi: 10.1093/applin/aml035

- MacWhinney, B. (2012). The logic of the unified model. Chapter 13. In: The Routledge Handbook of Second Language Acquisition. Gass, S. M. & Mackey, A. (Eds).
- MacWhinney, B. (2015). Emergentism. Chapter in: Dabrowska, E, Divjak, D, (Eds.) Handbook of Cognitive Linguistics. New York, NY: Mouton-DeGruyter.
- MacWhinney, B. (2017). A shared platform for studying second language acquisition. *Language Learning*, 67, 254-275. doi: 10.1111/lang.12220
- MacWhinney, B. (2019). Neuroemergentism: Levels and constraints. *Journal of Neurolinguistics*, 49, 232-234. doi:10.1016/j.jneuroling.2018.04.002
- MacWhinney, B. & O'Grady, W. The handbook of language emergence. Wiley Blackwell. West Sussex, UK.
- Martin, K. I. & Ellis, N. C. (2012). The roles of phonological STM and working memory in L2 grammar and vocabulary learning. *Studies in Second Language Acquisition*, 34(3), 379–413. doi:10.1017/S0272263112000125
- Mårtensson, J., Eriksson, J., Bodammer, N.C. et al. (2012). Growth of language- related brain areas after foreign language learning. *NeuroImage*, 63(1): 240–244. doi:10.1016/j.neuroimage.2012.06.043.
- McLaughlin, J., Osterhout, L. & Kim, A. (2004). Neural correlates of second-language word learning: minimal instruction produces rapid change. *Nature Neuroscience*, 7, 703–704. doi:10.1038/nn1264
- Miyake, A. & Friedman, N. P. (1998). Individual differences in second language proficiency: Working memory as language aptitude. In A. Healy & L. Bourne (eds.), *Foreign language learning*. Mahwah, NJ: Lawrence Erlbaum, 339–364

- Nichols, E. S. & Joanisse, M. F. (2016). Functional activity and white matter microstructure reveal the independent effects of age of acquisition and proficiency on second-language learning. *NeuroImage*, *143*, 15–25 <https://doi.org/10.1016/j.neuroimage.2016.08.053>
- Onnis, L., Truzz, A., & Ma, X. (2018). Language development and disorders: Possible genes and environment interactions, *Research in Developmental Disabilities*, *82*, 132-146. <https://doi.org/10.1016/j.ridd.2018.06.015>
- Paap, K. R., & Sawi, O. (2014). Bilingual advantages in executive functioning: Problems in convergent validity, discriminant validity, and the identification of the theoretical constructs. *Frontiers in Psychology*, *5*, 962. <http://dx.doi.org/10.3389/fpsyg.2014.00962>.
- Paap, K.R., Johnson, H.A., and Sawi, O. (2015). Bilingual advantages in executive functioning either do not exist or are restricted to very specific and undetermined circumstances. *Cortex*, *69*, 265–278. doi:10.1016/j.cortex.2015.04.014.
- Petitto, L.A., Berens, M.S., & Kovelman, I. et al. (2012). The ‘perceptual wedge hypothesis’ as the basis for bilingual babies’ phonetic processing advantage: new insights from fNIRS brain imaging. *Brain and Language*, *121*(2), 130–143. doi:10.1016/j.bandl.2011.05.003
- Pliatsikas, C. 2020. Understanding structural plasticity in the bilingual brain: the dynamic restructuring model. *Bilingualism: Language and Cognition*, *23*, 459–471.
- Reiterer, S. M. (2019). Neuro-Psycho-Cognitive Markers for Pronunciation/Speech Imitation as Language Aptitude. Chapter in Z. Wen, P. Skehan, A. Biedroń, S. Li, R. L. Sparks (Eds.), *Language Aptitude: Advancing Theory, Testing, Research and Practice*. Taylor&Francis/Routledge
- Rimfield, K., Dale, P. S., & Plomin, R. (2015). How specific is second language-learning ability? A twin study exploring the contributions of first language achievement and intelligence to

- second language achievement. *Translational Psychiatry*, 5(9), e638.
<https://doi.org/10.1038/tp.2015.128>
- Rottschy, C., Langer, R., Dogan, I., Reetz, K., Laird, A. R., Schulz, J. B., Fox, P. T., Eickhoff, S. B. (2012). Modelling neural correlates of working memory: A coordinate-based meta-analysis. *Neuroimage*, 60, 830-846. <https://doi.org/10.1016/j.neuroimage.2011.11>.
- Skehan, P. (2015). Working memory and second language performance. In Wen, Z., M. Mota & A. McNeill (eds.), 189–201.
- Stein, M., Winkler, C., Kaiser, A., & Dierks, T. (2014). Structural brain changes related to bilingualism: Does immersion make a difference? *Frontiers in Psychology*, 5(1116), 1-7.
doi: 0.3389/fpsyg.2014.01116
- Sun, X., Li, L., Ding, G., Wang, R., & Li, P. (2019). Effects of language proficiency on cognitive control: Evidence from resting-state functional connectivity. *Neuropsychologia*, 129, 263-275.
- Uddin, L. Q. (2021). Cognitive and behavioural flexibility: Neural mechanisms and clinical considerations. *Nature Reviews*, 22, 167–179. <https://doi.org/10.1038/s41583-021-00428-w>
- Ullman, M. (2001). A neurocognitive perspective on language: The declarative/procedural model. *Nature Reviews Neuroscience*, 2, 717–726. <https://doi.org/10.1038/35094573>
- Ullman, M. T. (2016). The declarative/procedural model: A neurobiological model of language learning, knowledge, and use. In G. Hickok & S. A. Small (Eds.), *Neurobiology of language* (pp. 953–968). London: Academic Press. <https://doi.org/10.1016/B978-0-12-407794-2.00076-6>

- Vaughn, K. A., & Hernandez, A. E. (2018). Becoming a balanced, proficient bilingual: Predictions from age of acquisition & genetic background. *Journal of Neurolinguistics*, 46, 69–77. <https://doi.org/10.1016/j.jneuroling.2017.12.012>
- Vaughn, K.A., Ramos Nuñez, A. I., Greene, M. R., Munson, B., Grigorenko, E. L., & Hernandez, A. E.x (2016). Individual differences in the bilingual brain: the role of language background and DRD2 genotype in verbal and non- verbal cognitive control. *Journal of Neurolinguistics* 40: 112–127. doi:10.1016/j.jneuroling.2016.06.008.
- Weber-Fox, C. M. & Neville, H. J. (2007). Maturational Constraints on Functional Specializations for Language Processing: ERP and Behavioral Evidence in Bilingual Speakers. *Journal of Cognitive Neuroscience*, 8(3). <https://doi.org/10.1162/jocn.1996.8.3.231>
- Wen, Z. E., Biedrón, A., & Skehan, P. (2017). Foreign language aptitude theory: Yesterday, today and tomorrow. *Language Teaching*, 50(1), 1-31. doi:10.1017/S0261444816000276
- Werker, J. F., & Tees, R. C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, 7, 49-63.
- Yang, J. & Li, P. (2012). Brain networks of explicit and implicit learning. *PLoS One*, 7(8). doi: 10.1371/journal.pone.0042993
- Yang, J. & Li, P. (2019). Mechanisms for auditory perception: A neurocognitive study of second language learning of Mandarin Chinese. *Brain Sciences*, 9(139), 1-15. doi:10.3390/brainsci9060139
- Zhang, X., Yang, J., Wang, R., & Li, P. (2020). A neuroimaging study of semantic representation in first and second languages. *Language, Cognition, & Neuroscience*. doi: 10.1080/23273798.2020.1738509