

CONCEPTUAL REVIEW ARTICLE

The Neurocognitive Underpinnings of Second Language Processing: Knowledge Gains from the Past and Future Outlook

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Abstract: The past decades have seen an explosion of research using electrophysiological or neuroimaging techniques for studying the neurocognitive underpinnings of second language (L2) processing. Although this field has a shorter history than does research on language learning more generally, important insights into the neurocognitive basis of L2 processing have driven it to the center stage of language science. In this target article for *Language Learning*'s 75th Jubilee volume, I illustrate the field's impressive achievements by selectively reviewing electrophysiological and neuroimaging research on L2 processing and bilingual brain organization. I also review changing perspectives in the field (including individual difference and experience-based perspectives, neural network approaches, neuroplasticity, and L2-learning related neural changes) and identified challenges, promises, and future directions (revisit native-speaker benchmark, increase linguistic diversity, enhance ecological validity, intensify research on child L2 learners' brain, adopt lifelong approach to L2 learning) that can lead to a better understanding of the neural underpinnings of L2 learning and processing.

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Introduction

Since the publication of early studies using electrophysiological and neuroimaging techniques to study second language (L2) learning and processing in the mid to late 1990s, research on the bilingual brain has generated much enthusiasm. In this target article for *Language Learning*'s 75th Jubilee volume, I review selected topics on L2 learning and processing in the bilingual brain that have moved the field forward and led to important insights into the neurocognitive underpinnings of L2 processing across the lifespan. In line with *Language Learning*'s aim to contribute to the understanding of language learning, I will focus on developments in understanding the neurocognitive basis of L2 learning. This implies that I will not discuss topics in the broader field of advanced bilingualism that have seen major theoretical and empirical developments in the past 25 years, such as neurocognitive studies on language control and domain-general cognitive tasks (for an excellent review, see Tao et al., 2021), neurocognitive contributions to the bilingual cognitive advantage debate (Bialystok & Craik, 2022; Paap et al., 2015, and commentaries), or the neurocognitive basis of codeswitching (Van Hell et al., 2018).

I have organized this conceptual review as follows. I start with describing two classical (series of) studies published in the late 1990s that illustrate two major neurocognitive techniques used to study the neurocognitive underpinnings of L2 learning and processing in the past decades, electroencephalography (EEG)/event-related potentials (ERPs; Weber-Fox & Neville, 1996) and positron emission tomography (PET)/functional magnetic resonance imaging (fMRI; e.g., Chee et al., 1999; Kim et al., 1997; Klein et al., 1995; Perani et al., 1998); each sparked highly productive lines of research. For each line of research, I then illustrate the field's impressive achievements by outlining several major insights acquired over the past 25 years, discuss some changing perspectives, and identify challenges, promises, and future directions. But first I discuss a foundational theoretical perspective underlying these and many studies on the neurocognitive basis of L2 learning and processing, the critical period hypothesis.

Critical Period Hypothesis for L2 Learning

Shortly after publication of the first studies using neurocognitive techniques to examine L2 learning and processing, *Science* identified the question "Why are

there critical periods for language learning?” as one of the 125 critical questions for the next 25 years (Kennedy & Norman, 2005). This question ensued from the observation that “children pick up languages with ease while adults often struggle to learn train station basics in a foreign language” (Kennedy & Norman, 2005, p. 93), mentioning the monitoring of brain activity as a window to shed light on the biological basis of L2 learning.

Whether there is a critical period for language learning, or in fact one for any human skill, is a longstanding and fundamental question in human development. Understanding language as a biological system governed by maturational stages in an organism’s lifespan during which the nervous system is especially sensitive to certain environmental stimuli, Penfield and Roberts (1959) proposed a critical period for language development, later popularized by Lenneberg (1967) in his book *Biological Foundations of Language*. The notion of a critical period for language learning was adopted by research on L2 learning in the 1980s (instigated by Johnson & Newport’s, 1989, classical study) and has remained a popular, yet highly disputed, research topic ever since (e.g., Berken et al., 2017; Birdsong, 2018; DeKeyser, 2013; Singleton & Lesniewska, 2021; Steinhauer, 2014). Behavioral studies focused on the timing of the critical period, the shape of the function that relates age of acquisition (AoA) to ultimate L2 attainment, and the existence of multiple, separate critical periods for different aspects of language. Neurocognitive studies started out with the question of whether there is a biologically based critical period for L2 learning after which learners are unable to acquire and process their L2 in a way that is qualitatively similar to native language (L1) speakers. This biologically constrained learning has typically been related to a loss of brain plasticity after a critical (or sensitive) period for language learning in childhood, with the implication that adult L2 learning is driven by fundamentally different neurocognitive mechanisms than is child L1 development. Key constructs leading this research have been AoA and nativelike ultimate attainment—using attainment scores of native speakers as decisive yardsticks.

As I will show, decades later this quest evolved into a better understanding of the intricacies of the relationships between neuroplasticity, language experience, and variation in L2 learning outcomes (e.g., DeLuca et al., 2019; Steinhauer, 2014). Facilitated by advances in neurocognitive methodologies and better synergy between language science and neuroscience (cf., Grosjean et al., 2003), researchers learned that language learning is not constrained to an age-bound critical period; rather, numerous studies provided evidence for continued neuroplasticity for language learning in the adult brain. At the very least, critical periods were reformulated as changes in neural plasticity, or

qualitative shifts in the recruitment of neural systems, in the course of L2 learning. Before moving to discussing neurocognitive research on L2 learning and processing, I briefly outline the primary neuroscientific methods used in this field.

Electroencephalography and Functional Magnetic Resonance Imaging Methodologies

As this paper features studies using EEG/ERP and fMRI techniques, a basic description of these techniques follows; for more details on EEG/ERP and fMRI in L2 research, see Dickson and Pelzl (in press) and Kousiae and Klein (in press). EEG records electrical activity in the brain over time, measured at the scalp. ERPs reflect very small voltage changes in brain activity that are time-locked to the onset of specific events such as a critical word in a sentence. They provide an online millisecond-by-millisecond record of the brain's electrical activity during cognitive processing as it unfolds over time. ERP studies on L2 processing have often used a violation paradigm and compared processing of a violation of a (morpho)syntactic principle (e.g., subject–verb agreement as in *The girl *walk to school*) or semantic anomaly (e.g., *The nail *walks to school*) with processing their correct counterparts.

An ERP signal comprises a sequence of positive and negative peaks related to stimulus processing. These ERP components are characterized by polarity, latency, amplitude, scalp distribution, and a functional description of mental processes that they are assumed to reflect—the functional significance of ERP components remains a topic of continued research and discussion. The main components associated with sentence processing are the early-left anterior negativity (ELAN), left anterior negativity (LAN), N400, and P600.

- The ELAN is an anterior negativity between 150–250 ms, often lateralized over the left hemisphere, and has been associated with automatic early syntactic parsing and building up an initial phrase structure (e.g., Hahne & Friederici, 1999; cf. Steinhauer & Drury, 2012).
- The LAN is an anterior negativity, often left-lateralized, in the 300–500 ms range, and has been associated with the integration of morphosyntactic information in a sentence structure (e.g., Caffarra et al., 2017; Molinaro et al., 2011).
- The N400 is a centro-parietal negative-going wave in the 300–500 ms range. The N400 is taken to reflect semantic access that depends on several factors, for example, the strength of the semantic relation between the target word and the preceding sentence (e.g., Federmeier,

2021; Kutas & Federmeier, 2011; for further discussion, see Bornkessel-Schlesewsky & Schlesewsky, 2019).

- The P600 is a large positive-going wave that emerges around 500–600 ms poststimulus and extends for several hundred milliseconds and has a centro-parietal distribution. The P600 has been associated with syntactic reanalysis and repair following the detection of a syntactic violation (e.g., Osterhout & Holcomb, 1992) or processing syntactically complex structures (Kaan et al., 2000); for recent discussions on the functional significance of the P600, see Kuperberg et al. (2020), Leckey and Federmeier (2020), Tanner et al. (2017), and, in L2 learners related to their subjective grammars, see Lemhöfer et al. (2020).

L2 learners' ERP signatures have been found to sometimes deviate from the aforementioned patterns (as further discussed below) and can vary with L2 experience and proficiency (Steinhauer et al., 2009). In particular, ERP responses to (morpho)syntactic violations may not emerge in beginning L2 learners, can show N400-like signatures in intermediate learners, and can show a more canonical P600 (sometimes delayed and with smaller amplitudes), sometimes preceded by a LAN, in advanced L2 learners.

EEG/ERP techniques enable fine-grained temporal analyses of brain activation patterns but have a poor spatial resolution. fMRI is a noninvasive hemodynamic neuroimaging technique that has a high spatial resolution (but a poor temporal resolution) and provides insight into the spatial organization of neural activity during task performance. Blood releases oxygen to active neurons at a greater rate than it releases oxygen to inactive neurons. The blood-oxygen-level-dependent (BOLD)-signal, detected in fMRI, reflects changes in magnetism caused by increased oxygen-rich blood flow to active brain regions. The BOLD-signal is used as an index of the level of activity of particular brain areas as a result of conducting a specific cognitive task (see Soares et al., 2016, for more details on fMRI physics and methodology). The majority of task-based fMRI studies on L2 processing examined the function of specific brain regions, but in line with general trends in neuroimaging research, the focus has gradually been shifting toward characterizing functional networks that connect different brain regions (see the section Neural Network Approaches). I now turn to empirical work that used electrophysiological and neuroimaging techniques to explore the neurocognitive underpinnings of L2 learning and processing.

Electrophysiological Studies on L2 Learning and Processing: Setting the Stage

The seminal work by Weber-Fox and Neville (1996) was among the first published studies that used the EEG/ERP technique to examine L2 processing and tested the critical period hypothesis. Using the violation paradigm, adult Chinese learners of L2 English (with different AoAs: 1–3, 4–6, 7–10, 11–13 years, or after 16 years) read sentences with a semantic or syntactic violation (phrase structure or specificity constraint violation) and their correct counterparts. ERPs to semantic violations (N400s) of all L2 learner groups were comparable to those of native English speakers, although L2 learners with AoA of 11 years or higher had slightly delayed N400 peak latencies. In contrast, L2 learners' ERP profiles for syntactic violations, irrespective of AoA, differed from those of native speakers and appeared less nativelike with increasing AoA. Specifically, in native speakers, syntactic violations elicited an ELAN followed by a LAN and P600. By contrast, L2 learners showed a LAN (bilaterally distributed in L2 learners with AoA of 11 years or older), followed by a nativelike P600 in L2 learners with an AoA before 11 years but a delayed (AoA 11–13 years) or no (AoA > 16) P600 in later L2 learners. Weber-Fox and Neville (1996) concluded that maturational changes constrain the neural systems that are relevant for language learning and processing and that puberty marks a significant point in development for language learning capacity. They further concluded that subsystems specialized for semantic and syntactic processing display different sensitive periods and that particularly the syntactic system is constrained by maturational processes.

Weber-Fox and Neville's (1996) seminal study sparked a wealth of neurocognitive work studying neural plasticity and late L2 learning (for reviews, see Hernandez & Li, 2007; Van Hell & Tokowicz, 2010; Steinhauer, 2014; Caffarra et al., 2015),¹ and new insights, two of which I discuss in the next two sections: the impact of L2 proficiency (section Age of Acquisition or L2 Proficiency?) and (dis)similarity of L2–L1 structures (section L1–L2 Similarity–Dissimilarity of Grammatical Structures). The linguistic domain on which much of this work focused is L2 grammatical processing, therefore the next two sections mainly describe ERP studies on L2 (morpho)syntactic processing.

Age of Acquisition or L2 Proficiency?

The bilinguals tested in Weber-Fox and Neville's (1996) study not only differed in AoA of L2 English but also in their life-long exposure to English and L2 proficiency. Because of this confound, the observed differences between AoA groups cannot be unequivocally attributed to AoA and may have been

driven at least partly by differences in L2 proficiency (Caffarra et al., 2015; Steinhauer, 2014; Van Hell & Tokowicz, 2010). Pakulak and Neville (2011) directly addressed the AoA–L2 proficiency confound in Weber-Fox and Neville (1996) by comparing German late learners of L2 English with L2 proficiency-matched native English speakers. Phrase structure violations, relative to correct controls, elicited a bilateral and prolonged anterior negativity followed by a P600 in native speakers but elicited only a P600 (more widespread spatially and temporally) in L2 learners. Pakulak and Neville (2011) concluded that syntactic processes are sensitive to maturational constraints, corroborating Weber-Fox and Neville's (1996) findings that even highly proficient L2 speakers rely on different neural mechanisms during syntactic processing from those on which native speakers rely.

Arguably, disentangling AoA and L2 proficiency effects by comparing L2 learners with proficiency-matched native speakers is not the optimal method for isolating AoA from L2 proficiency effects in L2 processing. An alternative approach is to compare groups of L2 learners who vary in L2 proficiency but are matched on AoA (e.g., Bowden et al., 2013; Hanna et al., 2016; Rossi et al., 2006). For example, Bowden et al. (2013) tested English classroom learners of L2 Spanish who started Spanish classes at the same age (12–14 years) and did not differ in the amount of classroom exposure to Spanish until the age of 17 years. Tested in university, the low-intermediate L2 proficiency group had two semesters of L2 Spanish classroom experience in university, and the advanced proficiency group had nearly seven semesters of L2 Spanish classroom experience and one to two semesters of immersion experience in a Spanish-speaking country. Syntactic word order violations in L2 Spanish sentences (reversing nouns and verbs) elicited a LAN–P600 effect in advanced L2 learners (similar to L1 Spanish speakers tested on the same materials), whereas low-intermediate L2 learners showed a left anterior to centro-anterior positivity followed by a centro-posterior to posterior positivity in these time windows. Semantic violations elicited similar N400 effects in all groups. Bowden et al.'s (2013) findings exemplify the overall pattern that ERP signatures associated with L2 syntactic processing are modulated by L2 proficiency, with higher-proficiency L2 learners often displaying patterns that come close to those of native speakers, whereas ERP responses of lower-proficiency L2 learners may display both qualitative and quantitative differences.

The above studies treated AoA and L2 proficiency as categorical measures for classifying specific groups of learners. Several recent studies have treated these variables as continuous measures in their experimental design and analysis (e.g., Fromont et al., 2020; Meulman et al., 2015; Nichols & Joanisse,

2019). Using general additive modeling, Meulman et al. (2015) treated age as a continuous variable and studied the (nonlinear) ERP pattern over time to examine potential latency effects. Russian and Polish advanced learners of L2 German, with a wide range of L2 AoA, listened to grammatically correct and incorrect sentences containing violations of nonfinite verbs and grammatical gender agreement. Verb agreement violations elicited a P600 in native German speakers and in all bilinguals irrespective of their AoA. Gender agreement violations elicited a P600 in bilinguals with an AoA up to 20 years, whereas bilinguals with a higher AoA showed a posterior negativity in this time window. Importantly, the general additive modeling analysis revealed that AoA effects were linear and did not show any evidence of a discontinuity, which argues against the critical period hypothesis (for analogous reasoning based on behavioral evidence, see, e.g., Birdsong, 2018).

More recently, Fromont et al. (2020) recorded EEG while late L2 learners of French and French native speakers read sentences that were correct or contained a syntactic-category error, a semantic anomaly, or both. Analyses based on a traditional group design, comparing the group of late L2 learners with the group of native speakers, showed that ungrammatical sentences elicited a typical biphasic LAN–P600 in native speakers and an N400 in L2 learners, a qualitative difference in line with the critical period hypothesis. Importantly, however, individual brain data modeling using a random forests approach revealed that learners' L2 proficiency and amount of L2 exposure were the most reliable predictors explaining L2 learners' ERP responses, whereas AoA was the least important variable.

Other approaches that have been adopted for studying the impact of L2 proficiency on EEG/ERP signatures associated with L2 syntactic processing, while keeping AoA constant, are longitudinal studies of L2 learners (e.g., Gabriele et al., 2021; McLaughlin et al., 2010; Osterhout et al., 2006; White et al., 2012) and studies using artificial languages or miniature natural languages to track proficiency-related changes within a short timeframe (e.g., Batterink & Neville, 2013; Citron et al., 2011; Friederici et al., 2002; Grey et al., 2018; Morgan-Short et al., 2010, 2012; Pereira Soares et al., 2022; for review, see Morgan-Short, 2020). Combining the benefits of a longitudinal design and teaching an artificial (and manipulable) language, Morgan-Short et al. (2010, 2012) taught adults Brocanto2, an artificial language whose syntactic rules conform to natural-language universals. Learners received explicit training (metalinguistic explanation and meaningful examples) or implicit training (only meaningful examples). After the first and after the third and final training session, ERP responses to sentences with morphosyntac-

tic violations (noun–adjective and determiner–noun gender agreement violations; Morgan-Short et al., 2010) and syntactic violations (word order violations; Morgan-Short et al., 2012) were collected. At lower proficiency levels, these violations elicited an N400 in the implicit group but no significant ERP response in the explicit group (with the exception of a late N400 for noun–adjective violations). Different ERP signatures were observed as learners' proficiency increased. At higher proficiency levels, noun–adjective (morphosyntactic) violations elicited an N400, and determiner–noun (morphosyntactic) violations elicited a P600 in both implicit and explicit learners; syntactic violations elicited a bilateral anterior negativity followed by a P600 in the implicit group and an anterior positivity followed by a P600 in the explicit group. These qualitative changes in ERP patterns paralleled changes in ERP signatures in the course of L2 learning as also had been observed in longitudinal studies with classroom learners (e.g., Gabriele et al., 2021; McLaughlin et al., 2010; Osterhout et al., 2006; White et al., 2012) and indicated that ERP signatures associated with (morpho)syntactic structures change toward more nativelike patterns with increased proficiency levels.

In conclusion, since Weber-Fox and Neville's (1996) seminal study, the field has developed different approaches for examining the effects of AoA and L2 proficiency. Together these studies have demonstrated that variability in L2 proficiency (which may or may not relate to variability in AoA) modulates ERP signatures associated with L2 grammatical processing, leading to the overall conclusion that high-proficiency L2 learners often display patterns that approach native speakers' processing, whereas low-proficiency L2 learners' ERP responses display quantitative and qualitative differences.

L1–L2 Similarity–Dissimilarity of Grammatical Structures

Although Weber-Fox and Neville's (1996) seminal study examined ERPs with respect to two types of syntactic violations—phrase structure violations and specificity constraint violations, they did not systematically manipulate whether these syntactic structures are similar or dissimilar to corresponding structures in bilinguals' L1. Decades of research in the field of L2 acquisition has provided evidence that L1 knowledge impacts L2 learning and that similarities and dissimilarities between L1 and L2 systems are at the root of negative and positive crosslinguistic transfer effects (for review, see McManus, 2021). This has also become an important research topic in ERP studies published after Weber-Fox and Neville's (1996) study, with most studies comparing L2 learners' processing of L2 grammatical structures that are similar or different

in their L1 with native speakers' processing of these same grammatical structures (for review, see Caffarra et al., 2015).

A prominent theoretical basis in ERP studies on crosslinguistic transfer in L2 grammatical learning and processing is MacWhinney's (2005) unified competition model for L2 learning (for alternative models, see, e.g., universal grammar-based generative perspectives such as the failed functional features hypothesis or the full transfer/full access theory; e.g., Hawkins & Chan, 1997; Schwartz & Sprouse, 1996; for a different perspective, see Clahsen & Felser's, 2006, shallow structure hypothesis). The unified competition model postulates that when grammatical features are similarly instantiated in L1 and L2, L2 learners can easily and effectively apply L1 knowledge to learn and process L2 structures, and positive transfer takes place. In contrast, negative transfer occurs when linguistic features are present in L1 and L2 but are differently instantiated, which may lead to online competition between the languages. For syntactic structures unique in the learner's L2, there is no transfer or competition from L1, in which case L2 cue strength (i.e., the level of availability and reliability) will determine how well these L2 structures will be learned.

In a first ERP study that manipulated L1–L2 grammatical overlap to directly test the predictions of the competition model, Tokowicz and MacWhinney (2005) presented native English speakers enrolled in beginning Spanish classes with Spanish sentences containing syntactic violations and correct controls. The critical structures were formed similarly (auxiliary omission) or differently (determiner number agreement) in Spanish and English or were unique to Spanish and absent in English (determiner gender agreement). Even though behavioral grammaticality judgement accuracy was at chance for all constructions (see also McLaughlin et al., 2004), ERP data revealed P600 effects in response to violations for the similar and unique structures but not for the dissimilar structure. Tokowicz and MacWhinney concluded that learners are able to process certain aspects of L2 syntax, even in the early stage of L2 learning, but that this knowledge depends on the similarity between the L1 and the L2 systems, in line with the competition model.

Subsequent studies paralleled the finding of nativelike P600 effects when L2 structures are expressed similarly in L1, whereas for L2 grammatical structures that are expressed differently in L1 or are unique to L2, findings were more mixed. To exemplify the latter, some studies observed that L2 learners demonstrated no P600 or a reduced or differently timed P600 relative to native speakers (e.g., Carrasco-Ortíz et al., 2017; Erdocia et al., 2014; Foucart & Frenck-Mestre, 2011, 2012; Rossi et al., 2014; Sabourin & Stowe, 2008),

whereas others did not observe marked differences between (advanced) L2 learners and native speakers (e.g., Alemán Bañón et al., 2014; Gillon Dowens et al., 2011; White et al., 2012). Occasionally, N400 effects were observed in response to dissimilar or unique L2 constructions (e.g., Foucart & Frenck-Mestre, 2012), which aligned with longitudinal studies (e.g., Gabriele et al., 2021; McLaughlin et al., 2010; Osterhout et al., 2006) or individual brain-based studies (Tanner et al., 2014) showing that in earlier L2 learning stages learners can show an N400 to syntactic violations that gradually shifts to a classic (nativelike) P600 effect as proficiency increases (in line with Steinhauer et al.'s, 2009, stage-wise model).

Remarkably few studies examined how L1–L2 (dis)similarity impacts language processing at different levels of proficiency within one learner population using either cross-sectional (e.g., Alemán Bañón et al., 2018; Diaz et al., 2016; Mickan & Lemhöfer, 2020) or longitudinal (e.g., Morgan-Short et al., 2010, 2012; Osterhout et al., 2006) designs. These studies are particularly insightful for tracking L2 proficiency-related changes in the transfer of L1 structures to L2 syntactic processing. For example, Mickan and Lemhöfer (2020) tested three groups of German learners of L2 Dutch who had been immersed in Dutch for three months (beginning learners), 10 months (intermediate learners), or at least 18 months (advanced learners), and a group of native Dutch speakers. The study measured behavioral and ERP responses for Dutch sentences containing violations of syntactic constructions that were similar (subordinate clause inversion) or dissimilar (sentence-final double infinities) across Dutch and German and their correct counterparts. ERPs to similar constructions provided evidence in line with Steinhauer et al.'s (2009) stage-wise model: Beginning learners showed an N400-like negativity, whereas intermediate and advanced learners showed P600s similar to those of native speakers. Dissimilar constructions also elicited an N400-like negativity in beginning learners but delayed and smaller P600s in intermediate and advanced learners relative to native speakers. Importantly, these data indicate that progression through the L2 learning stages is not solely driven by L2 proficiency but can also be modulated by the level of (dis)similarity of syntactic structures across L2 and L1 and the extent to which L2 learners can transfer knowledge of their L1 to L2. Progression from qualitatively different ERP signatures (from N400 to P600) to nativelike P600 effects appears slower for dissimilar syntactic structures that do not enable L1–L2 knowledge transfer.

Electrophysiological Studies: Current Status and Future Directions

The above-reviewed EEG/ERP studies have provided evidence that L2 grammatical learning and processing is not only modulated by AoA but also by L2 proficiency and similarity, dissimilarity, or uniqueness of L2–L1 structures. Variability in these factors yields quantitative and qualitative differences in ERP signatures associated with L2 syntactic processing beyond Weber and Neville's (1996) original conclusion that "maturational changes significantly constrain the development of the neural systems that are relevant for language" (p. 231). More generally, these findings also question the conclusion that AoA effects necessarily point to a loss of brain plasticity during a specific period early in life (a point I return to later when discussing neuroimaging studies). In this section, I outline three underexplored yet promising topics for further advancing insights into the neurophysiological correlates of L2 syntactic processing: (a) studying interindividual variation in ERP response profiles, (b) examining oscillatory neural dynamics and neural network activation patterns associated with L2 processing, and (c) revisiting the notion of the gold standard of the native speaker as the ultimate goal for L2 learning.

Individual Differences Beyond Age of Acquisition and L2 Proficiency and Individual Variation in Event-Related-Potential Response Profiles

Future EEG research should embrace a wider range of individual differences measures beyond AoA and L2 proficiency and study, for example, how variability in cognitive functions, language learning aptitude, and motivation impacts electrophysiological correlates of L2 processing; this point also applies to neuroimaging studies as will be discussed in the section Neuroimaging Studies on L2 Learning and Processing: Setting the Stage (e.g., Turker et al., 2021). Recent studies using behavioral measures demonstrated that these cognitive and personality variables can affect L2 learning and learning trajectories over time (e.g., Dörnyei, 2014; Linck et al., 2014; Saito et al., 2020; Sparks, 2012). An emergent literature using EEG methodology has given evidence that, for example, cognitive control (e.g., Covey et al., in press; Pulido, 2021; Zirnstein et al., 2018), working memory (e.g., Gabriele et al., 2021; but see Dong et al., 2022), declarative and procedural memory abilities (e.g., Faretta-Stutenberg & Morgan-Short, 2018; Morgan-Short et al., 2014), and motivation to speak the L2 as a native speaker (Tanner et al., 2014) also impact L2 sentence processing. For example, L1 English learners of L2 Spanish with better working memory skills exhibited greater ERP grammaticality effects (P600) to noun–adjective number violations, with a similar trend for noun–adjective gender violations (Gabriele et al., 2021). These findings suggest that work-

ing memory, responsible for control, regulation, and active maintenance of information when processing potentially distracting information (e.g., Linck et al., 2014), shapes learners' neural sensitivity to linguistic features (including anomalies) during online L2 sentence processing. Relatedly, Zirnstein et al. (2018) observed that bilinguals with better inhibitory control abilities were better able to generate predictions of upcoming information and to navigate prediction errors during online L2 sentence processing.

Because individual differences in ERP signatures have only recently begun to be studied in neurolinguistic research (see Tanner et al., 2018), more systematic evidence is needed to better understand how individual difference variables affect the neural time course of L2 grammar learning and processing as it unfolds in real time. Questions that warrant further research include identifying which individual difference variables shape the processing of a given linguistic phenomenon and the extent to which a given individual difference variable affects multiple linguistic phenomena. Using advanced linear models, such as hierarchical mixed effects or generalized linear mixed effects models, that relate the magnitude or peak latency of ERP components (e.g., the P600) with individual difference measures is a valuable approach for providing further insight into how variation in learners' cognitive, language-experience, and personality variables affects L2 processing (e.g., Covey et al., 2022; Dong et al., 2022; Nichols & Joanisse, 2019; Zirnstein et al., 2018; see Meulman et al., 2015, for a generalized additive modeling approach and Fromont et al., 2020, for a random forests approach). A further advancement is that these techniques treat individual difference variables as continuous measures rather than as categorical variables, which enables more fine-grained and nuanced insights into the dynamics of individual difference variables on the ERP signal that cannot be obtained by traditional group-based ANOVAs.

ERP studies on syntactic processing in L2 learners have typically analyzed and reported grand-average waveforms. These group-based grand averages often misrepresent L2 learners' individual ERP signatures that can vary substantially across individuals in terms of the amplitudes and latencies of ERP components. This individual variability is lost when calculating a grand average ERP waveform. More specifically, biphasic negative–positive grand mean ERP waveforms (N400 followed by P600) have been found to be the result of averaging across individuals who actually show different ERP response profiles (e.g., Beatty-Martínez et al., 2021; Grey, 2023; Tanner et al., 2014; Qi et al., 2017). For example, testing proficient Spanish–English bilinguals, Tanner et al. (2014) observed an N400–P600 grand average waveform in

response to subject–verb agreement violations in L2 English, but computations of the response-dominance index revealed that these violations actually elicited N400s in some individuals and P600s in others (see Tanner et al., 2014, for details on computing the response dominance index). As a qualitative transition from N400 to P600 effects has been identified as a hallmark of L2 learning, the group-based grand average may obscure that some, but not all, learners have already progressed to a more advanced proficiency level. In addition, individual variability may also underlie the lack of statistical power for reliably detecting a given (canonical) ERP component at the group-based grand average level: The absence of a nativelike P600 in the group-based grand average waveform of L2 learners may actually reflect individual variability in ERP response profiles.

Apply Advanced Electroencephalography Techniques to Study L2 Processing

Most EEG-based neurocognitive research on L2 learning and processing used the ERP technique. This field would be further enhanced by adapting new advancements in EEG techniques, including analyses of oscillatory neural dynamics using time frequency representations (e.g., Bakker et al., 2015; Kielar et al., 2014; Lewis et al., 2016; Litcofsky & Van Hell, 2017; Rossi & Prystauka, 2020) and of neural network activation patterns associated with L2 processing (e.g., Pérez et al., 2015). Time frequency representations index the ongoing oscillatory dynamics of the EEG signal and reflect the (de)synchrony of functional neural networks. In these analyses, power, or activity, in different frequency bands (delta, theta, alpha, beta, and gamma) in response to stimuli is of interest; power changes in each frequency band are associated with specific cognitive processes (for more details and application to L2 research, see Rossi et al., 2023). For example, testing English late L2 learners of Spanish and Spanish native speakers, Rossi and Prystauka (2020) investigated neural oscillatory activity associated with the processing of Spanish gender and number (expressed via agreement on clitic pronouns), which is a structure unique to the learners' L2 Spanish and does not occur in English. Overall, the L2 learners and native speakers showed qualitatively similar oscillatory patterns: power decreases in alpha and beta frequency bands for gender violations, in the beta band for number violations, and in theta, alpha, and beta frequency bands for combined gender and number violations (see Rossi & Prystauka, 2020, for a detailed exposition of possible cognitive processes associated with power changes in the different bands). Importantly, L2 learners differed from native speakers in the duration of these neural oscillatory effects in that

they persisted in native speakers and ceased earlier in L2 learners. Rossi and Prystauka explained this difference in the time course of the neural oscillatory signal in terms of a Hebbian cell assembly framework for language processing (e.g., Hebb, 1949; Pulvermüller, 1996; Strijkers, 2016), which posits a biphasic time course for activation of neural assemblies: a fast ignition phase (linked to target identification) and a reverberation phase (linked to grammatical reprocessing and verbal working memory). Rossi and Prystauka hypothesized that differences between L2 learners and native speakers manifest themselves in the reverberation phase as decreased duration of the oscillatory signal to morpho-syntactic violations in the L2 learners, possibly related to a limited availability of working memory resources while processing in their L2.

As a further example, Pérez et al. (2015) employed a complex network analysis approach to study time-varying topographical properties of functional networks as extracted from EEG data. This analysis is based on graph theory and models the brain as a graph whose nodes represent different regions and links connecting nodes represent functional (or structural) connections. Pérez et al. presented Spanish sentences containing article–noun gender agreement violations and their correct counterparts to highly proficient English–Spanish bilinguals (all late L2 learners) whose accuracy in detecting article–noun gender agreement violations in Spanish sentences was nearly perfect and equal to native Spanish speakers. The complex network analysis yielded no differences between bilinguals and native speakers on the correct sentences. However, for L2 learners but not for native speakers, a lower degree of parallel information transfer and a slower propagation between regions was found for incorrect relative to correct sentences. This indicated that even when highly proficient L2 learners' accuracy scores are similar to native speakers, their neural network activation pattern can be configured differently from that of native speakers. This type of analysis is a promising avenue for gaining nuanced insights into individual variation in L2 learning trajectories and variables that potentially modulate brain network activation patterns associated with L2 syntactic processing.

Revisit the Native-Speaker Benchmark for L2 Attainment

Weber-Fox and Neville's (1996) seminal study and many subsequent neurocognitive studies on grammatical processing in L2 learners considered, explicitly or implicitly, native speaker performance as the ultimate goal and benchmark of L2 learning. Typically, as also reviewed above, researchers compared L2 learners' ERP patterns to native speaker ERP signatures to assess the extent

to which L2 learners' performance was nativelike and whether the L2 learners' grand average waveform was qualitatively and quantitatively comparable to native speakers' grand average waveform (Freunberger et al., 2022).

Adopting a native-speaker benchmark for L2 attainment is problematic in multiple ways; this point also pertains to neuroimaging studies that used a native-speaker benchmark to interpret L2 learners' neural organization (see the section Neuroimaging Studies on L2 Learning and Processing: Setting the Stage). First, setting the native speaker as the gold standard basically embraces, and perpetuates, a deficiency model of L2 learning and bilingualism (e.g., Cook, 2016). Second, L2 learners do not develop into native speakers of their L2, but rather they develop as bilinguals and become bilingual speakers of their L2 (e.g., Ortega, 2018). Ubiquitous evidence of coactivation of the bilinguals' two language systems during language processing entails that bilinguals' basic machinery is fundamentally different from that of (monolingual) native speakers, and this may, or may not, materialize in differences in performance. Indeed, if L2 learners show a nativelike P600 in response to a grammatical violation, this does not necessarily imply that the L2 learners' underlying neural activation patterns and their neurocognitive processing are identical to those of native speakers (cf., Pérez et al., 2015). As I further discuss in the section Neural Regions Involved in L1 and L2 Processing: Role of Age of Acquisition and L2 Proficiency, there is mounting evidence of L2 learning-induced structural changes in bilingual brains, that is, differences in grey matter density and cortical thickness, as well as white matter integrity between language areas, in bilingual versus monolingual brains. Third, there is compelling evidence against the idealized notion of the native speaker possessing a complete and uniform language, whose performance can serve as the gold benchmark of ultimate language attainment. This evidence has been built up from empirical work employing behavioral measures as well as EEG methodology (e.g., Grey et al., 2017; Pakulak & Neville, 2010; Tanner & Van Hell, 2014). For example, testing monolingual native speakers, Tanner and Van Hell (2014) observed that individuals' ERP response profiles for grammatical violations (subject–verb agreement and verb tense) varied between being either negativity-dominant (more similar to an N400) and positivity-dominant (more similar to an P600). That grammatical violations can elicit an N400 in monolingual native speakers challenges the assumption that an N400 effect in L2 learners reflects nonnativelike performance.

Researchers have learned in the past decades that L2 learning trajectories are multifaceted, and research should embrace their complexity rather than narrow these down to the perfect path toward the idealized native speaker.

Moving beyond the idealized native speaker and the native speaker benchmark entails a paradigm shift in L2 research (for recent discussions, see the special issue edited by Vulchanova et al., 2022; also see Rothman et al., 2022). I highlight several approaches here realizing there is no perfect solution and that these options are not always, and widely, available.² For example, Ortega (2018) argued we should “refuse to engage in subordinating comparisons and nativespeakerism” (p. 13) and proposed that, if comparisons or benchmarks are needed, a nonsubordinate option should be chosen, for example by comparing sequential bilinguals who learned L2 at a later age with simultaneous bilingual speakers of these same languages. Another approach is to compare L2 learners against their native-speaking selves: Adopting a within-participant design in L1 English learners of L2 Spanish, Grey (2023) compared group-based and individual-based ERP processing profiles for semantic and grammatical violations in their L2 Spanish with L1 English. A third example is to adopt a language-experience perspective and use a spectrum of bilingual experiences as regressors in the statistical design (discussed in more detail in the section Bilingual Brain and Experience-Based Perspectives). Finally, longitudinal or cross-sectional designs can be used to track the neural basis of L2 learners’ trajectories over time when they are learning a natural language or an artificial language. Using such designs, researchers can also compare language learning trajectories in different groups of learners to examine how specific learner variables impact learning—with, in artificial or miniature languages, the added bonus of maintaining experimental control over the nature of language structures being studied, their (dis)similarity to participants’ known other language(s), and the amount and type of language exposure.

Neuroimaging Studies on L2 Learning and Processing: Setting the Stage

At around the same time that Weber-Fox and Neville (1996) published their seminal ERP study, the first studies using neuroimaging techniques (PET or fMRI) to investigate the neural regions involved in L1 and L2 processing in bilinguals were published (Chee et al., 1999; Kim et al., 1997; Klein et al., 1995; Perani et al., 1998). These first studies examined whether neural substrates involved in L2 and L1 processing are the same, benefiting from technological advances to study this classical question (Paradis, 2004) under experimentally controlled conditions rather than depending on experiments of nature (as in lesion studies). Klein et al. (1995) asked French–English bilinguals who had learned L2 English after the age of 5 years to generate a rhyme word, a synonym, or the translation of a word presented in their L1 or their L2. Klein

et al. observed increased activity in the left inferior frontal and dorsolateral prefrontal cortices in each generation task relative to the baseline condition (in which a L1 or L2 word was repeated), irrespective of whether words were generated in L1 or L2, or within or across languages. There was no evidence that L2 was represented differently from L1. Chee et al. (1999) reached a similar conclusion for early and late Mandarin learners of L2 English.

A different conclusion was reached by Kim et al. (1997) and Perani et al. (1998). Asking late and early bilinguals to silently generate speech in L1 or L2, Kim et al. (1997) concluded that, for late bilinguals, the frontal cortical language areas (most notably the left inferior frontal gyrus) were spatially separated for L2 and L1, whereas for early bilinguals, L1 and L2 were more likely to be represented in highly overlapping frontal cortical areas. Likewise, in Italian late L2 English learners with moderate proficiency, Perani et al. (1998) observed that listening to L1 Italian stories engaged the temporal lobes and temporoparietal cortex more extensively than did listening to L2 stories. However, when presenting similar tasks to Italian late L2 English learners with higher proficiency and to proficient Spanish–Catalan early bilinguals, Perani et al. found no differences in neural areas activated for L1 and L2. On the basis of these combined findings, Perani et al. concluded that attained L2 proficiency is a stronger determinant of L2 cortical representation than is AoA.

These initial and groundbreaking neuroimaging studies opened up multiple lines of research, recently examined through meta-analyses, on bilingual brain organization and neural regions involved in L1 and L2 processing (for review, see Sulpizio et al., 2020; see the section Bilingual Brain Organization and Neural Regions Involved in L1 and L2 Processing) and the impact of AoA and L2 proficiency on language representation in the bilingual brain (for review, see Cargnelutti et al., 2019; see the section Neural Regions Involved in L1 and L2 Processing: Role of Age of Acquisition and L2 Proficiency); these studies examined bilinguals who had learned their L2 at some point earlier in life, typically at home or at school. Another line of research examined the neural correlates of lexical and grammatical learning under experimentally controlled learning conditions, typically in the laboratory, using stimuli such as pseudowords, artificial grammars, or miniature languages (for review, see Tagarelli et al., 2019; see the section Neuroanatomical Substrates of Lexical and Grammar Learning).

Bilingual Brain Organization and Neural Regions Involved in L1 and L2 Processing

Sulpizio et al. (2020) conducted a comprehensive meta-analysis on neuroimaging data published between 1995 and 2018 to identify the neural areas that are associated with bilinguals' processing of phonology, lexicosemantics, and grammar in L1 and L2. Out of the original set of over 700 articles, their meta-analysis was ultimately based on 52 peer-reviewed papers that reported activation for $L1 > L2$ or $L2 > L1$ in highly proficient adult bilinguals. Overall, the analysis showed that L1 and L2 processing engages similar neural structures, as little evidence for extensive selective activation for either L1 or L2 was obtained. Notwithstanding this general pattern, different patterns were observed for the three linguistic levels, in particular for lexicosemantic processing compared to phonological and grammatical processing. Lexicosemantic processing in L1 showed a widespread activation pattern of cortico-subcortical regions (cortical: bilateral inferior frontal gyrus, left medial frontal gyrus, left middle temporal and parahippocampal gyri, left precuneus, bilateral superior and left inferior parietal lobules, right angular gyrus, right fusiform gyrus, left posterior cingulate, and left superior occipital gyrus; subcortical: left thalamus, left amygdala, right caudate head) that aligns with the semantic network identified by meta-analyses on monolingual language processing (e.g., Binder et al., 2009). Lexicosemantic processing in the L2 yielded activation of regions that exceeded the classical semantic network and also included regions associated with cognitive control-related functions (bilateral globus pallidus [part of the basal ganglia], right insula, and right cerebellum), such as selective attention and monitoring that may support the processing of semantic information in L2.

In contrast, grammar processing in L1 and L2 involved largely similar neural structures in L1 and L2, and this pattern was also found for phonological processing. More specifically, grammar processing in L1 and L2 mainly engaged frontal/basal ganglia networks that have been associated with procedural-related circuits (and no involvement of medial temporal structures more associated with declarative memory, cf. Ullman's declarative/procedural model, e.g., Ullman, 2020). Phonological processing in both L1 and L2 involved frontal regions (more widespread for L2), that is, regions that are key components of the dorsal pathway in dual-stream models of speech processing (e.g., Hickok & Poeppel, 2007; Saur et al., 2008) and that are involved in translating acoustic speech signals into articulatory representations.

Neural Regions Involved in L1 and L2 Processing: Role of Age of Acquisition and L2 Proficiency

Another recent meta-analysis on neural structures recruited during L1 and L2 processing in bilinguals focused specifically on the impact of AoA and L2 proficiency on language representation in the bilingual brain (Cargnelutti et al., 2019). This meta-analysis included 57 peer-reviewed studies (reporting 74 experiments with 1,048 participants in total) on lexicosemantic, phonological, and grammar processing (unlike Sulpizio et al., 2020, these domains were not analyzed separately). Separating early from late bilinguals (L2 AoA at age 6 years or later), this analysis showed that in both early and late bilinguals the classical left-hemisphere language areas were involved in both L1 and L2 processing, as well as regions supporting general executive functions (including left presupplementary motor area and dorsolateral prefrontal cortex). Importantly, during L2 processing, the neural areas activated in late bilinguals were more widespread than in early bilinguals, for language areas (including the inferior frontal gyrus and pars orbitalis, left superior temporal gyrus, and left inferior and superior parietal lobes), and for areas related to control and executive functions (left presupplementary motor area, anterior cingulate cortex, dorsolateral prefrontal cortex, and bilateral insula), the right cerebellum, and some right hemisphere posterior areas in the occipital cortex and angular gyrus. Interestingly, L1 processing also recruited more widespread neural areas in late than in early bilinguals. A subsequent analysis that included only data of highly proficient early and late learners (to remove the possible confound with L2 proficiency in the overall analysis) paralleled the finding that L2 processing activated more widespread areas in late than in early bilinguals.³

Neuroanatomical Substrates of Lexical and Grammar Learning

The above studies examined the neural correlates of processing naturally learned languages (e.g., learned at home or at school) that generally take years to acquire. A different, and quite popular approach is to model the longer-term trajectory of natural language learning under experimentally controlled learning conditions through the use of artificial linguistic stimuli and systems (e.g., pseudowords or artificial grammars) or miniature language systems (e.g., foreign-language words; see Ettlinger et al., 2016; Morgan-Short, 2020). Unlike natural languages, these artificial/miniature language stimuli are learnable within a short period of time and can be experimentally controlled for the nature of the stimuli (e.g., Chen et al., 2021) and training (e.g., Batterink & Neville, 2013; Morgan-Short et al., 2010) as well as for the amount and timing of exposure to the learner (e.g., Bakker-Marshall et al., 2021; Takashima et al.,

2014; Weber et al., 2016). Tagarelli et al. (2019) conducted a meta-analysis of 46 peer-reviewed studies (entailing 60 participant groups and 769 adult participants selected out of 251 papers) that examined the neural correlates of lexical and grammatical learning in experimentally controlled language training studies using PET or fMRI techniques. The analysis demonstrated overlapping neural activation for lexical and grammar learning in the frontal and parietal cortices. More specifically, overlapping activation was found bilaterally in and around the inferior frontal gyrus (including the pars opercularis and pars triangularis), the precentral gyrus, the anterior insula, as well as the supplementary motor area (more dorsal and posterior for lexical learning, and more ventral and anterior for grammar learning). Lexical and grammar learning also involved the left posterior parietal lobe, including the superior parietal lobule and the angular gyrus of the inferior parietal lobule.

The analyses further indicated that the ventral occipito-temporal cortex is particularly involved in lexical learning, in particular the left inferior temporal gyrus and the left fusiform gyrus. These areas in the inferior temporal and occipital lobes are part of the ventral pathway in dual-stream models of speech processing (e.g., Hickok & Poeppel, 2007; Saur et al., 2008) that has been proposed to be particularly important for mapping sounds to meanings and thus critical for lexicosemantic learning and processing. Finally, grammar learning, but not lexical learning, engaged the left caudate nucleus and left anterior putamen, parts of the basal ganglia. The basal ganglia have been widely associated with procedural learning functions (e.g., Kreitzer & Malenka, 2008) that in turn have been proposed to underlie grammatical learning in Ullman's declarative/procedural model (e.g., Ullman, 2020; see Tagarelli et al., 2019, for further discussion how the meta-analysis outcomes support this model).

Neuroimaging Studies: Current Status and Future Directions

As I reviewed in the section Neuroimaging Studies on L2 Learning and Processing: Setting the Stage, the early PET/fMRI studies that explored the organization of the bilingual brain have inspired a wealth of studies that provided valuable insights into the functional areas associated with L2 learning and processing. How variability in AoA and L2 proficiency impact the neural underpinnings of L2 learning and processing has been, and still is, a major focus in fMRI research. Parallel to the upsurge of functional neuroimaging studies over the past decades (reviewed in the sections Bilingual Brain Organization and Neural Regions Involved in L1 and L2 Processing, Neural Regions Involved in L1 and L2 Processing: Role of Age of Acquisition and L2 Proficiency, and Neuroanatomical Substrates of Lexical and Grammar

Learning), the field has seen other significant advances that inform the neural underpinnings of L2 learning and processing. Next, I briefly outline three topics (selected out of many possible topics) that build on and extend these insights, and that bear promising avenues for future neuroimaging research: (a) neural network approaches, (b) structural MRI studies, and (c) bilingual experience-based approaches.

Neural Network Approaches

In the past decade, neuroimaging studies of language gradually shifted from describing the function of specific brain regions to identifying the spatial and temporal dynamics of functional networks that connect different brain regions (Bressler & Menon, 2010). This shift has also led to neural network paradigms becoming increasingly applied to L2 learning and processing (Kousiae & Klein, in press; see Li & Xu, 2023, for a review of computational modeling in L2 processing and learning). An attested method for characterizing neural networks is to establish resting-state functional connectivity that is considered to reflect intrinsic functional organization of the brain (e.g., Fox & Raichle, 2007). More specifically, resting-state fMRI (rs-fMRI) determines the functional connections between anatomically distant neural areas at rest, that is, when the participant does not engage in task-driven behavior. Of the neural networks that have been identified using rs-fMRI, two have been specifically associated with language processing, including L2 processing: the language network (e.g., Fedorenko & Thompson-Schill, 2014; Friederici, 2017; Hertrich et al., 2020) and the default-mode network (Fox & Raichle, 2007; Gordon et al., 2020).

Resting-state fMRI for determining the functional connectivity between neural areas has become increasingly used in L2 learning and bilingualism research (e.g., Berken et al., 2016; Chai et al., 2016; Claussenius-Kalman et al., 2020; Liu et al., 2017; Sulpizio et al., 2020; Veroude et al., 2010; for an EEG-based resting-state connectivity approach, see, e.g., Bice et al., 2020; for a structural connectivity approach using diffusion tensor imaging, see, e.g., Rossi et al., 2017). For example, Veroude et al. (2010) assessed functional connectivity before and after presenting a weather report movie in Chinese to Dutch participants (who reported no knowledge of Chinese). Based on an auditory old–new word recognition task presented after the weather report, participants were divided into two groups: nonlearners and learners (whose *d*-prime scores showed some sensitivity to distinguishing new Chinese words from previously heard Chinese words). After exposure to the Chinese weather report, functional connectivity between the left and right supramarginal gyrus was stronger for learners than for nonlearners, consistent with a role of the left

supramarginal gyrus in the storage of phonological forms (pretraining, the correlation between these areas was similar for both groups; see Chai et al., 2016, who used rs-fMRI pretraining to predict learner-differences in learning outcomes following a 12-week intensive language learning). Comparing highly proficient simultaneous and sequential bilinguals (learned L2 after the age of 5 years), Berken et al. (2016) used a seed-based rs-fMRI approach to examine the functional connectivity profile of the inferior frontal gyrus (IFG), a key structure implicated in L2 processing (see the section Neural Regions Involved in L1 and L2 Processing: Role of Age of Acquisition and L2 Proficiency). Compared to sequential bilinguals, simultaneous bilinguals had stronger functional connectivity between the IFG in left and right hemispheres, as well as between the IFG and brain areas implicated in language control (including dorsolateral prefrontal cortex, inferior parietal lobule, and posterior cerebellum). Moreover, connectivity between left and right IFG and right inferior parietal lobule correlated negatively with AoA in sequential bilinguals—the earlier L2 was acquired, the stronger the resting state connectivity. Greater resting state functional connectivity between left and right IFG was also associated with reduced neural activation in left IFG during speech production, interpreted to reflect greater neural efficiency in the IFG. Berken et al. (2016) concluded that the degree of functional connectivity within the language control network is shaped by age of L2 acquisition, indicating that the bilingual brain's intrinsic functional patterns are influenced by the developmental timeline of L2 learning.

Other recent neural network approaches that are promising to provide novel insights into the bilingual brain include (but are not restricted to) the use of localizer tasks to functionally characterize language regions in the brain on an individual level (Jouravlev et al., 2021) and network science approaches that use a data-driven quantitative approach to modeling language structure (Zaharchuk & Karuza, 2021).

L2 Learning and Structural Changes in the Brain

The past decade has also seen a surge of evidence that L2 learning and usage are accompanied by structural changes in the brain. Such structural changes can be examined via cortical thickness and shape and/or volumetric changes in grey matter in cortical and subcortical regions involved in language learning, processing, and control as well as in changes in the diffusivity of white matter tracts connecting these regions. Much of the evidence on neuroplasticity and structural changes associated with L2 learning in adults comes from training studies and longitudinal studies (for reviews, see DeLuca et al., 2019; Li et al.,

2014; for review of transcranial stimulation techniques applied to enhance L2 learning, see Balboa-Bandeira et al., 2021). As reviewed by Li et al. (2014), structural changes in the brain are mirrored by functional neural patterns shown in fMRI studies. More specifically, L2 learners with substantial L2 learning experience, through formal instruction or laboratory-based training studies, generally show increases in grey matter volume and/or density in cortical and subcortical areas that fMRI studies have identified as being involved in language learning and processing (the left hemisphere inferior frontal gyrus, middle frontal gyrus, superior temporal gyrus, anterior temporal lobe, and inferior parietal lobule, the right hemisphere hippocampus and cerebellum, and the left/bilateral caudate nucleus) and language monitoring and control (frontal-striatal network in the left hemisphere involving the inferior frontal gyrus, anterior cingulate cortex, inferior parietal lobule, and caudate nucleus). For example, Mårtensson et al. (2012) tested students enrolled in an intensive language training. Compared to a control group of nonlearners (matched in age and cognitive abilities to the learners), after three months of training, the learners showed increased cortical thickness in language-related regions in the left hemisphere fronto-temporal cortex (inferior and middle frontal gyrus, and superior temporal gyrus), as well as increased right hippocampal volume (hippocampal changes are linked to language learning and memory; Davis & Gaskell, 2009; Takashima et al., 2014). Moreover, learners who had attained higher proficiency levels showed increased cortical thickness in the left superior temporal gyrus and right hippocampus, which Mårtensson et al. suggested may indicate that plasticity of these brain regions (higher structural malleability) relates to language learning talent.

These and related findings on L2 learning/bilingualism-induced neuroplasticity are captured in Pliatsikas's (2020) dynamic restructuring model that classifies bilingualism-induced effects in neural plasticity into three stages of language learning and use that are each associated with distinct structural changes: initial exposure, consolidation, and peak efficiency (for recent reviews, see Kořenář & Pliatsikas, in press, and Abutalebi & Green's, 2016, updated language control model).

Finally, the literature on structural changes in the brain induced by L2 learning raises the question of whether these structural neural changes are reflected in functional neural patterns within the same individual. So far, few studies on L2 learning have used multimodal brain imaging methods within the same participants to explore functional and structural neuroplasticity associated with L2 learning (for exception, see, e.g., Wang et al., 2020). Multimodal imaging studies (combining task-based fMRI, rs-fMRI, and/or structural MRI

within the same learners) are obviously resource-demanding but will also be an important step forward for revealing L2-learning related neural changes and for significantly enhancing understanding of brain dynamics and neural plasticity associated with L2 learning.

Bilingual Brain and Experience-Based Perspectives

The surge of studies on L2 learning and brain plasticity has been paralleled by an increased conceptualization of bilingualism as a gradient measure. Rather than describing bilinguals along the dimensions of AoA or L2 proficiency, researchers have increasingly called for taking a more holistic experience-based perspective that not only includes AoA and L2 proficiency but also current language use, environmental context (including immersion), quality and quantity of switching between languages, language dominance rather than L1 versus L2, and the like (e.g., Beatty-Martínez & Titone, 2021; Gullifer et al., 2018; Litcofsky & Van Hell, 2017; Marian & Hayakawa, 2021; Navarro-Torres et al., 2021; Pliatsikas et al., 2020; Sulpizio et al., 2020). Relatedly, acknowledging that variation among bilinguals in terms of learner-internal and learner-external variables yields variable L2 learning outcomes and processing strategies, researchers have increasingly shied away from categorizing bilinguals into dichotomous groups (e.g., early vs. late bilinguals; low-proficiency vs. high-proficiency L2 learners). For example, Gullifer, Titone, and colleagues introduced the construct of language entropy for measuring individual differences in the social diversity of language use, emphasizing the communicative context of language use (e.g., Gullifer et al., 2018); the entropy value increases with a more balanced, and higher diversity of, language use. Using seed-based resting state functional connectivity, Gullifer et al. (2018) observed that language entropy modulated resting-state connectivity for a widespread set of neural regions: Functional connectivity between the anterior cingulate cortex and bilateral putamen and between the left caudate and bilateral superior temporal gyrus was stronger for bilinguals with higher social diversity of using their two languages (i.e., higher entropy score). As these areas have been implicated with cognitive control, attention, and conflict managing (e.g., Abutalebi & Green, 2016; Blanco-Elorrieta & Pylkkänen, 2018), Gullifer et al. interpreted these findings as implying that higher (vs. lower) degrees of diversity in social language use are related to a broadly distributed set of neural networks implicated in proactive control and context monitoring.

Future Avenues of Research: Some Questions and Desiderata

Since the early EEG and neuroimaging studies on L2 processing were published in the mid to late 1990s, thousands of neurocognitive studies on L2 learning and bilingual processing have been published—I have reviewed only a fraction of this literature. Are there any remaining, or underexplored, questions to address in the coming decade? Yes, many! In this final section I highlight a few (out of many!) avenues for further research.

Increase Linguistic Diversity in Neurocognitive Research

Decades of neurocognitive studies yielded important insights into the neural underpinnings of L2 processing—but only for a fraction of the world's languages and for a narrow sample of the world's L2 learners. As an illustration, only 16 languages were tested as L1 or L2 in the studies included in Sulpizio et al.'s (2020) meta-analysis that spanned two decades of fMRI research: English, German, Dutch, Swedish, Finnish, Spanish, French, Italian, Ladin, Catalan, Basque, Russian, Macedonian, Chinese, Japanese, and Korean (with Ladin, Macedonian, Russian, and Basque tested in one study). Notably absent are the hundreds of different languages spoken in (profoundly multilingual) continents, including Africa, Asia, and Central-South Americas, as well as signed languages (beyond American and British signed languages; Emmory et al., 2016; MacSweeney et al., 2008; cf. Li et al., 2015) and indigenous languages (cf. Blasi et al., 2022). In profoundly multilingual societies such as on the African continent, speakers have learned different languages at different ages, for varied purposes, and in different settings. Importantly, rather than testing whether insights accrued from testing L2 learners and bilinguals living in the United States or Europe generalize to other populations (an approach often taken in attempts to globalize research efforts, Adetula et al., 2022), researchers should examine language learning and processing in these multilingual contexts and transfer these newly acquired insights to transform research on L2 learning and processing.

Enhance Ecological Validity of Neurocognitive Research

Traditionally, neurocognitive research has been conducted under well-controlled conditions in the laboratory, which challenges the ecological validity of research outcomes. Despite constraints imposed by scanning equipment, efforts have been made to enhance the ecological validity of neurocognitive research, and these efforts have also entered the field of L2 learning and processing. This has included efforts to create more naturalistic stimulus materials (e.g., Alemán Bañón & Martin, 2021; Blanco-Elorrieta & Pykkänen, 2018),

to measure brain activity in mimicked real-life settings such as noisy environments (e.g., Rammell et al., 2019) or interactive discourse situations (e.g., Kaan et al., 2020), and to apply neurocognitive techniques in field settings or in the L2 learning classroom (Van Hell, 2020). For example, presenting English learners of L2 Spanish with Spanish and English sentences in noisy or in quiet conditions, Rammell et al. (2019) observed an increase in activation in auditory perceptual processing regions, in particular the posterior superior temporal sulcus, for L2 Spanish sentences in noise, whereas they observed no increase in activation related to perceptual processing for L1 English sentences presented in noise. Furthermore, Kaan et al. (2020) observed that the speaker identity of a silent bystander (who presented themselves as a monolingual or bilingual speaker) affected the neural responses associated with bilinguals' reading of code-switched sentences. These studies indicated that neural correlates associated with bilinguals' language processing can be different when tested in more naturalistic settings.

In addition, despite the extensive behavioral literature on L2 instruction, researchers know relatively little about the impact of various instruction methods (beyond work on implicit and explicit learning, see the section Age of Acquisition or L2 Proficiency?), study abroad versus classroom learning (Faretta-Stutenberg & Morgan-Short, 2018), or the nature of feedback and reinforcement (Bultena et al., 2017) on the neural correlates of L2 learning. Finally, an ecological reality of L2 learning and neural plasticity is forgetting and attrition, and future research may expand current (but still limited) knowledge on the neural dynamics of language attrition (e.g., Bergmann et al., 2015; Steinhauer & Kasparian, 2020).

Intensify Research on Child L2 Learners' Brains

Since *Science* wondered why “children pick up languages with ease while adults often struggle to learn train station basics in a foreign language” (Kennedy & Norman, 2005, p. 93), and in their quest for monitoring brain activity to understand the biological basis of L2 learning, researchers have gained significant insights into why learning foreign languages is challenging for adults and into variables that modulate such challenges. However, the past decades of neurocognitive research paid substantially less attention to why “children pick up languages with ease” (and whether that is even true) and the developing bilingual brain. There has been work on the neural basis of speech perception and phonological development in infants growing up with two languages (e.g., Ferjan Ramírez et al., 2017; for review, see Ortiz Villalobos et al., in press) but a smaller literature on the neural correlates of children's L2 lex-

ical (e.g., Conboy & Mills, 2006; Ojima et al., 2005; Sirri & Rämä, 2019) and syntactic (e.g., Arredondo et al., 2019; Ip et al., 2017; Jasinska & Petitto, 2013) learning and processing. For example, using fNIRS neuroimaging, Arredondo et al. (2019) tested Spanish–English bilingual and English monolingual children (aged 8–11 years) who listened to correctly structured sentences and sentences with errors on earlier-acquired morphemes (*bake* + ing) and later-acquired morphemes (*bake* + ed/s). Both bilingual and monolingual children displayed greater left IFG activation for later- than earlier-acquired morphemes. Importantly, bilingual children showed more adultlike patterns of neural activity than did monolingual children, that is, more focal activity in left IFG, whereas monolingual children displayed a more distributed and bilateral pattern of frontal lobe activation. Arredondo et al. suggested that, as Spanish has a richer morphosyntactic structure than English, bilingual children may attend more to morphosyntax in English than do monolingual English children, in line with crosslinguistic transfer. Furthermore, although less proficient in Spanish, the bilingual children also displayed greater left frontal activation for later- versus earlier-acquired morpheme errors in Spanish sentences. Together these findings indicated that, relative to monolinguals, bilingual children's dual-language experience may advance neural specialization and the functionality of the left IFG to support more diverse linguistic input.

There is also an emerging literature on the effects of bilingualism on children's brain structure (e.g., Archilla-Suerte et al., 2018), including studies that have tracked the developmental trajectories of bilingualism-induced changes in brain structure using longitudinal (Mohades et al., 2015) or cross-sectional (Pliatsikas et al., 2020) designs. Notwithstanding the fascinating studies indicating that the systematic use of two languages during the critical years of neural plasticity may enhance neural computational abilities for language processing, researchers still have a lot to learn about the developing bilingual brain. This includes critical questions on how simultaneous and sequential bilingual language experiences modulate the neurodevelopmental course of language processing and organization in the young bilingual brain, whether and how crosslinguistic transfer optimizes bilingual children's neural system, and the extent to which bilingual children's neurodevelopmental trajectories differ qualitatively and/or quantitatively from those of their monolingual peers.

Epilogue

In the past decades, neurocognitive studies have yielded tremendous insights into the neural basis of L2 learning and processing and paved the way for inspiring new questions. Alongside the explosion of research and the advance-

ment of neurocognitive techniques, the field has educated a cohort of capable researchers, often bilingual themselves, who have been trained to conduct high-quality research on bilingualism and the brain. Reaching maturity without losing curiosity, this flourishing field is therefore strongly positioned to break new ground on the neurocognitive underpinnings of L2 processing.

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Notes

- 1 Although several recent meta-analyses have synthesized bilingual fMRI data (see the section Neuroimaging Studies on L2 Learning and Processing: Setting the Stage), aside from Caffarra et al.'s (2005) logistical regression analyses, to my knowledge, no meta-analysis has been published in this specific domain.
- 2 This does not imply that testing a native speaker group is never useful. In fact, native speaker data can be important for validating experimental designs, materials, and procedures. For example, if L2 learners do not show sensitivity to a particular manipulation, native-speaker data can help verify this is not due to methodological issues (e.g., flaws in stimulus materials) or an underpowered design.
- 3 The neuroimaging studies included in Cargnelutti et al.'s (2019) and Sulpizio et al.'s (2020) meta-analyses were more concerned with lexicosemantic processing than with grammar or phonological processing. This gap is relevant, as AoA effects have been argued to be particularly pronounced in the development of phonology and grammar (e.g., Mayberry & Kluender, 2018). Therefore, future fMRI research may focus more on how bilinguals process phonology and grammar in their L1 and L2 and on how variability in AoA and L2 proficiency impact the neural underpinnings of phonological and grammar processing.

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