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Time Slows Down in the Future: Aging and the Brain Rhythms of Language

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Abstract

Language is perhaps the most complex and sophisticated of cognitive faculties in humans. The neurobiological basis of language in the healthy, aging brain remains a relatively neglected topic, in particular with respect to basic aspects of grammar and meaning. In the face of major changes to the physiological infrastructure underpinning perception and higher cognition, core language functions are frequently retained in the elderly. Meanwhile, neurolinguistic models of language are often tested and refined with reference to system abnormalities (as in cases of language deficits or aphasias), but rarely with reference to the aging brain. This article outlines some major developmental stages in the neural architecture of language, and reviews the current state-of-the-art in research concerning how aging can result in distinct neural signatures of language. Certain differences in basic phrase and sentence processing strategies between children, young adults, and older adults can partly be explained by neurophysiological differences, and also divergences in core components of brain rhythms. Particular focus is placed here on spatiotemporal dynamics and neural oscillations, inter-brain coupling, 1/f neural noise, and neural entrainment. Exploring how language function changes with age can ultimately provide insights into the maturation and decay of basic properties of cortical computation.

Keywords: Neural oscillations; Brain dynamics; Syntax; Language; Aging; 1/f Noise

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1. Introduction

> ‘‘As a fond mother, when the day is o’er,
> Leads by the hand her little child to bed […]
> So Nature deals with us, and takes away
> Our playthings one by one, and by the hand
> Leads us to rest so gently, that we go
> Scarce knowing if we wish to go or stay,
> Being too full of sleep to understand
> How far the unknown transcends the what we know.’’
> Henry Wadsworth Longfellow, “Nature,” 1839

Modern linguistics has arrived at the general assumption that the human mind/brain applies a set of syntactic rules to recursively combine linguistic units into larger objects, deriving an unbounded array of hierarchically structured expressions, with humans inferring sentence meaning based on syntactic configuration (Chomsky, 1956, 1957, 1959; Everaert, Huybregts, Chomsky, Berwick, & Bolhuis, 2015; Hagoort, 2023; Mukherji, 2022; Murphy, 2015, 2016b, 2019, 2025b; Murphy & Woolnough, 2024). This capacity can be detected even in infancy (Crain, Koring, & Thornton, 2017; Perkins & Lidz, 2021), and alongside lexico-semantic knowledge it forms the basis for how language interfaces with other complex cognitive systems, including situation model construction, working memory, attention, controlling mental reference frames, and speech processing. While researchers disagree on how central grammatical knowledge is to the neural language architecture (Jackendoff & Audring, 2020), most agree that syntactic and semantic knowledge form essential components of the language network (Murphy & Shim, 2020; Murphy et al., 2023). Yet, much less has been said of the aging language system. Infants, children, and the elderly all exhibit varying degrees of linguistic competence and processing capabilities. Within the world of theoretical linguistics, Lasnik and Uriagereka (2022: 181) recently discussed “whether what we think of as different languages (which some of us appear to carry in our heads) involve literally different lexicons or portions of a single macrolexicon,” which can exhibit distinct levels of decay and transformation over time.

Approaching issues of neural implementation should be guided by what we know about the structure of the computational system of language. This system appears to be extremely simple at the level of structure building, with morphophonology adding considerable complexity to basic syntactic operations. Essentially, the system boils down to a single recursive combinatorial operation, MERGE, that acts upon a workspace and manipulates stored objects from memory (the lexicon), with concerns of structural relations taking precedence (Chomsky, Gallego, & Ott, 2019). Adhering to the criteria of simplicity as a feature inherent to system design is not unique to linguistics (Murphy, 2025b; Murphy, Holmes, & Friston, 2024a). In physics, two of the most fundamental equations arise from the simplest possible curvature-based structures in field theories. In gauge theory, the Yang−Mills Lagrangian uses the squared field strength tensor $F_{\mu\nu}F^{\mu\nu}$, a natural choice for measuring curvature. In General Relativity, the Einstein−Hilbert action employs the Ricci scalar curvature R, the simplest scalar derived from the curvature tensor. These two examples illustrate how minimal geometric principles—squaring curvature or using a scalar piece of it—lead to foundational physical theories. Within linguistics, we can take the simplest operation, MERGE, and derive the complexity of syntax, applying it to a newly selected object (External Merge) or one already part of the workspace (Internal Merge), to, respectively, derive lexical relations (predicate-argument structure, selection, etc.) and discourse relations (quantificational information, topic-focus, etc.). It is also worth noting that while a purely MERGE-based syntax is certainly desirable, there are likely other components of grammar that are needed to fully account for elements of syntax beyond local phases (Lasnik & Uriagereka, 2022).

The potentially species-specific nature of this component of language (recursive syntactic structure building, mapped to a conceptual system) may go some way to explain human (but not current artificial intelligence; Dentella, Günther, Murphy, Marcus, & Leivada, 2024) faculties for abstraction, reasoning, and compositionality (Marcus, 2001). For instance, if we take (1) a Rule (major premise), (2) a Case (minor premise), and (3) a Result (conclusion), Peircean deduction is defined as (1)-(2)-(3), while induction reverses (1) and (3). The more mysterious process of abduction—(3)-(1)-(2)—might have arisen in humans from increased abstraction capacities and the facility for symbolic thought, executively implemented via top-down lower frequency influences.

2. Rhythms and neural syntax

How best to approach this topic from a neurobiological perspective? In his book *Rhythms of the Brain*, György Buzsáki (2006) observes that spontaneous neuronal activity can be characterized by organized cycles of synchronized firing, and argues that self-emerged oscillatory timing is the fundamental organizer—the "neural syntax" (Buzsáki, 2010)—of neuronal information, accounting for a host of perceptual and cognitive faculties. This argument became more refined in a subsequent book (Buzsáki, 2019): brain rhythms help organize internal, generative models of the world that are in the game of predicting the experience of our sensorium. Neural oscillations contribute to the brain's goal of imposing a range of cognitive models onto sensory data in an effort to minimize revisions of beliefs about the world. The more refined, robust, and accurate the model, the less likely it will need revision.

With respect to their explanatory power over models of neuronal information transmission, brain rhythms "have come of age," as Buzsáki and Freeman (2015) put it. Brain rhythms reflect synchronized fluctuations in neuronal excitability and are grouped by frequency, with the canonical rhythms being delta (δ: $\sim$0.5$-$4 Hz), theta (θ: $\sim$4$-$8 Hz), alpha (α: $\sim$8$-$12 Hz), beta (β: $\sim$12$-$30 Hz), and gamma (γ: $\sim$30$-$200 Hz, split into low-, mid-, and high-γ). These are generated by various cortical and subcortical structures (Murphy, Hoshi, & Benítez-Burraco, 2022a), and form a hierarchical structure since slow rhythms phase-modulate the power of faster rhythms. Oscillations can fluctuate in amplitude, and do so in a gradual (phasic) or rapid (tonic) manner, with this behavior potentially reflecting coordinated computations. It has been known since at least Wilson and Bower (1991: 498) that "the phase and frequency of cortical oscillations may reflect the coordination of general computational processes within and between cortical areas." In general, slower rhythms are thought to synchronize distant brain regions, while faster γ rhythms are thought to activate local neuronal assemblies (Buzsáki & Draguhn, 2004). Oscillations have also been linked to the timing of cortical information processing (Klimesch, Sauseng, & Hanslmayr, 2007). Synchronous oscillatory activity has been suggested as a viable, neurobiologically feasible mechanism of top-down and bottom-up information propagation across cortical levels (Bressler & Richter, 2015).

Certain of the low-frequency phase codes invoked in language research (Murphy, 2024b) have also recently been shown to invoke frequency bands proven to maximize informational bit-rate (e.g., theta oscillations optimize a speed-precision trade-off in phase coding neurons, representing $\sim 1-2$ bits per/s), being more efficient at packaging information bits than higher frequency activity (Amil, Albesa-González, & Verschure, 2024). The neurocomputational infrastructure for language likely exploits the physics of the brain to encode abstract linguistic features.

Here, I use Buzsáki's (2006) focus on "rhythms of the brain" as a lens for exploring language function and representation in the naturally aging adult population (see Appendix for definitions of terms).

How different linguistic subcomponents transform during natural aging may relate to some very general aspects of brain dynamics, such as the regulation of high-frequency cortical activity by nonlocal, slower frequencies that execute a degree of top-down control over local processing (Buzsáki, 2019; Siebenhühner, Wang, Palva, & Palva, 2016), or the inter-areal synchronization of high-frequency activity across distant sites (Arnulfo et al., 2020). Another candidate here is interactional processes, like nonlocal phase-amplitude coupling (Soulat, Stephen, Beck, & Purdon, 2022), putatively capable of "packaging" units of information and recovering aspects of structure in distant sites (multiplexing) (Gross et al., 2013). These mechanisms seem amenable to treatment from linguistic theory, in particular with respect to long-distance grammatical relations (Lasnik & Uriagereka, 2022; Murphy, 2024b).

A recently developed neurocomputational architecture for the syntax-semantics component of language ("ROSE") proposes that the combinatorial power of MERGE is implemented via various interactions between brain rhythms, such as forms of cross-frequency coupling (Murphy, 2020, 2024a), forming a 'Universal Neural Grammar' (Murphy, 2025a). ROSE has also been shown to be compatible with a symbolic-connectionist approach (i.e., a hybrid model) for natural language, negotiating both the statistics and structure of language jointly, via parallel mechanisms and phase codes without the need to stipulate additional mechanisms to accommodate statistical inferences in addition to syntactic inferences (Murphy, 2024b). Although the finer details will not concern us here, very broadly, the architecture is built around low-frequency inter-regional phase-amplitude coupling, constructing multiple sets of syntactic and semantic features, with coupling across lateral frontotemporal language sites. β Rhythms in the inferior frontal cortex and high-frequency γ activity are also implicated in syntactic prediction and binding, respectively. This ROSE model has recently been supported by a number of empirical studies (for review, see Murphy, 2024b, 2025a).

As we will see, this scaffold for language comprehension can become subject to transformation over the course of healthy aging. ROSE is highly suited to adapting over the lifespan.

But before we approach this topic, an overview of some neural dynamics related to initial language development is needed, in order to properly contextualize and situate our understanding of what we mean by neural change and modification.

3. Developing language

Electrophysiological studies of infant and child language processing are crucial in furthering our understanding of the growth, development, and aging of the brain rhythms associated with language. To take one of the few current examples of this research, Schneider, Abel, Ogiela, Middleton, and Maguire (2016) showed θ and β power decreases in adults at, respectively, left frontal and parietal sites and right parietal sites during the processing of ungrammatical sentences. These results were not replicated in children, despite similar abilities to detect ungrammatical constructions. The children instead displayed an N400 effect at ungrammatical words, while adults showed a greater P600 effect (see also Schneider & Maguire, 2019). This suggests that syntactic neurocomputational mechanisms go through dynamically marked developmental stages.

Continuing this line of research, Leong et al. (2017) used electroencephalography (EEG) to show that infants not only entrain to the speech rhythm, but also appear better prepared for this than adults. Examining gaze-directed speech in which an adult spoke to an infant, partial directed coherence (PDC) was computed for all pairwise connections at all EEG frequencies. PDC is a directed measure of statistical causality (*How much does i predict j, independent of j's history*). Leong and colleagues showed that phase coupling was weaker when the adult speaker shifted their gaze away during speech in θ, α, and β. Consider also the findings reviewed in Goswami (2022). Goswami's lab has shown that stressed syllables in children's nursery rhymes, during perception, entrain to δ ("LON-DON"), individual syllables entrain to θ ("LON"), and the onset-rime structure entrains to β ("L," "ON"…), indicating that the perceptual and chunking apparatus for inferring linguistic structure is established early in childhood.

Much of the language neural network is already in place (and left-lateralized) before birth (see discussion of 'Universal Neural Grammar' in Murphy, 2025a), suggesting that exposure to speech is not necessary for the brain rhythms of basic syntax-semantics in language to develop (Dehaene-Lambertz, 2017). Winkler, Mueller, Friederici, and Männel (2018) explored the ontogenesis of syntactic embedding through implementing nested relations in tone sequences, hence minimizing perceptual and memory demands. They examined brain responses in 5-month-olds in two auditory oddball paradigms, presenting sequences with one or two levels of embedding, interspersed with deviant sequences violating embedding rules. Event-related potentials indicated that the infants were sensitive to the embedding violations (see also Perkins & Lidz, 2021).

Other age-related dynamics have been explored in recent literature. Brookes et al. (2018) used magnetoencephalography (MEG) to investigate stationary (i.e., time-averaged) and rapidly modulating (dynamic) electrophysiological connectivity in participants aged 9–25 years old. They gauged stationary functional connectivity via inter-regional coordination of neural oscillations. This was found to increase with age in α and β bands, particularly in bilateral parietal and temporo-parietal connections. Other changes in canonical bands can be found. Kurth et al. (2017) examined slow oscillations in sleep in a group of children ($n = 23$; 2–13 years) and showed that with increasing age, slow oscillations propagated across longer distances, with an average growth of 0.2 cm per year. The speed of the traveling waves remains unchanged across childhood. Since this area of neurobiological research is a recent development, further studies of child language processing within these frameworks will be needed to elaborate on these hypotheses any further, but I will simply note here that traveling waves have been hypothesized to index a number of linguistic processes pertaining specifically to workspace updating and the interfacing of linguistic information with distant cortical sites (Murphy, 2018, 2020, 2024a, 2024b).

As suggested here, low-frequency dynamics seem to be crucial in coordinating language comprehension, and they can be recorded with relative ease via extracranial recordings. However, interactional dynamics between frequencies also seem important. Attaheri et al. (2022) conducted a longitudinal EEG study in which 4-, 7-, and 11-month infants listened to nursery rhymes. They found that δ-band cortical tracking predicted infant language comprehension and production performance, as did θ-γ coupling. δ- and θ-driven phase-amplitude coupling was found at all ages, and γ displayed stronger coupling with low frequencies than β. Attaheri et al. (2022) did not find effects in the α band, which has been implicated in top-down attentional prediction and language encoding (Brodbeck, Hong, & Simon, 2018; Murphy, 2016a), potentially reinforcing the importance of this mechanism in mature language comprehension (Murphy, 2020). The maturation of dominant α bands across the cortex has been extensively explored (Klimesch, 1999). Resting-state EEG in children aged 4–12 years demonstrates a developmental increase in aperiodic-adjusted α peak frequency, but not aperiodic-adjusted α or β power, highlighting age-related functional changes within the developing brain (Hill et al., 2022).

Examining more global network dynamics, Doesburg, Tingling, MacDonald, and Pang (2016) recorded MEG in participants aged 4–18 performing a verb generation task. They calculated phase synchronization between brain regions and found task-dependent increases in synchronization in θ, α, and β, and network synchronization differences were observed between age groups. The authors also calculated network topologies for brain regions commonly associated with verb generation, and these were associated with age and language abilities. This provides support for the existence of an association between large-scale neurophysiological network synchronization and individual differences in the development of language abilities.

4. Age-related neural signatures of language comprehension

There are a number of general differences in basic language comprehension between children and older adults, in particular with respect to core components of chunking and structure-building. There are age differences in segmentation with respect to word-by-word self-paced reading (Stine, 1990), whereby younger readers spend more time on sentence-final words (“wrap-up,” consolidation over final syntactic node closures) than older readers, but older adults show similar reading time peaks to younger readers earlier in the sentence. A more general pattern that emerges is that when older readers show longer wrap-up at sentence-internal or sentence-final locations, age deficits in linguistic memory were minimized (Stine-Morrow, Miller, & Hertzog, 2006). When language is explicitly the focal point of testing, memory deficits are found in aging but are often variable (Johnson, 2003). Variation and individual differences in wrap-up effects have been found to be related to crystallized verbal skills, fluid-related processing capacity, and stored knowledge—all of which are related to language comprehension (Stine-Morrow & McCall, 2022). In addition, relative to skilled readers, adults with underdeveloped literacy skills dedicate more time to reading low-frequency words during sentence comprehension but dedicate less time to sentence wrap-up (Ng et al., 2020), utilizing a lexicality-driven parsing procedure as opposed to a more predictive, structure-driven one. Age-related differences can be found at all levels of basic sentence comprehension, with older adults exhibiting reductions in the incremental build-up of contextual information (Payne & Federmeier, 2018). Further afield, nonlinguistic event segmentation “may be less aligned with a hierarchical event structure among older adults relative to the young […] but older adults take equal advantage of cues to event boundaries to improve memory” (Stine-Morrow & McCall, 2022: 284).

As such, it would be predicted that chunking-related and memory-related language processes, and their concomitant implementation via the interactional dynamics afforded by brain rhythms, should be subject to age-related changes. Recent work has begun to elucidate the brain dynamics of the aging language faculty. Neurophysiological factors may partly contribute to intergenerational (mis)alignment in communication, across the young and the old, due to differences in inter-brain coupling (likely via coordinated low-frequency activity) (Dikker et al., 2022). This topic has become increasingly relevant given that social isolation during the COVID-19 pandemic disproportionately impacted the elderly (Dahlberg, 2021), and also given other recent work showing that subtle breakdowns in the network subserving language comprehension can be foretelling of conversion to Alzheimer’s disease from mild cognitive impairment (Mazaheri et al., 2018). Looking at inter-brain synchrony/coupling between people engaged in conversation (“hyperscanning”) can provide insights into these issues. Research using functional near-infrared spectroscopy (fNIRS) has shown that romantic couples, though not platonic friends, exhibit greater inter-brain coupling when discussing contentious topics compared to neutral topics (Long et al., 2021).

Aging also results in changes to white matter composition that impact the speed and strength of inter-areal neural communication (Diaz, Rizio, & Zhuang, 2016), with consequences for the rhythmic properties of neural response profiles for various perceptual and cognitive abilities. Older adults exhibit shifts in cerebral oscillatory patterns (Duffy, McAnulty, & Albert, 1993), which may explain differences in dyadic inter-brain coupling.

Other mechanisms pertaining to memory consolidation likely impact neural functions called upon by general language comprehension and consolidation. For example, older adults do not show the fine-tuned coupling of fast sleep spindles (12.5–16 Hz) to the peak of slow oscillations (0.5–1 Hz) present in younger adults, and rather display a slow spindle power increase (9–12.5 Hz) toward the end of the slow oscillation up-state. The precision of coupling between slow rhythms and fast sleep spindles promotes memory consolidation across all age groups (Muehlroth et al., 2019). Relatedly, noninvasive brain stimulation in a cohort of older adults (aged 60–76) suggests that a central feature of cognitive decline—deficits in working memory—emerges from disconnected local and long-range circuits instantiated via θ-γ phase–amplitude coupling in temporal cortex, and θ phase synchronization across frontotemporal cortex (Reinhart & Nguyen, 2019). This work follows earlier findings that increased working memory-evoked low γ power provides a neurophysiological marker in the healthy aging brain (Barr et al., 2014). Given that working memory decline appears to emerge from the inefficient and less rapid orchestration of rhythmic neuronal activity (pertaining to the timing of cortical computation) within large-scale cortical networks, and given that similar neural dynamics seem to index core linguistic processes (Murphy, 2024b; Murphy et al., 2022b; Murphy, Rollo, Segaert, & Hagoort, 2024b), it is expected that a decline in language function may be related to modulations in interactional oscillatory dynamics. Other groups have already shown that anodal-tDCS (transcranial direct current stimulation) administered to the left inferior frontal gyrus over 5 consecutive days may be a viable tool to enhance language learning abilities in the elderly (Perceval, Copland, Laine, Riggall, Ulm, & Meinzer, 2017).

Another general assessment in recent research is that properties of oscillations, functional connectivity, and signal complexity are clear biomarkers of both the healthy and pathological aging brain (Ishii et al., 2018). EEG-derived 1/f neural noise varies reliably as a function of age (Dave, Brothers, & Swaab, 2018), and noise also predicts N400 effects of lexical prediction in young and older adults; however, noise does not mediate age-related declines in other ERP effects, such as the post-N400 positivity (PNP), pointing to a specific impact on predictive processing. Interestingly, observed age-related differences in spectral power in canonical frequency bands (i.e., β) do not correlate with N400 effects of predictive accuracy (Dave et al., 2018). As such, invoking specific band effects cannot explain how 1/f neural noise mediates age-related changes in this particular neural index of prediction. This emphasizes the importance of studying the power spectrum as a "unified statistical representation of the signal" (Voytek et al., 2015: 13262). More generally, differences in 1/f neural noise appear to reflect age-related declines in population-level synchrony across neuronal networks, and are related to functions such as visual working memory decline (Voytek et al., 2015). The progressive flattening of the EEG power spectrum also appears to begin in early infancy, continuing into the first few months of life (Schaworonkow & Voytek, 2021), a development that seems to stay with us until old age.

Brain-behavior correlations in Price, Alain, and Bidelman's (2019) EEG study revealed that older adult comprehenders who were more resistant to the detrimental effects of noise also exhibited greater modulation of α phase coherence between clean and noise-degraded speech, relative to older adults who were subject to hearing loss. This indicates that α desynchronization indexes a release from inhibition and the flexible allocation of neural resources.

Younger and older language users may also differ in the order of linguistic parsing computations deployed during language comprehension: younger users seem to establish higher-order information earlier (sentence structure, grammatical predictions), whereas older users often parse lower-order linguistic information first (syllable structure, lexicality). Alternatively, the same order of computations may apply across young and old language users, but there may be differences in temporal delay between particular computations (Gwilliams & King, 2020).

Some relevant work in this connection comes from Penn, Ayasse, Wingfield, and Ghitza (2018). In young adults, the intelligibility of time-compressed speech can be rescued by "repackaging" the speech signal through the regular insertion of silent gaps, a process that restores correspondence to the θ oscillator. Penn et al. (2018) discovered a similar phenomenon for older adults, but the "rescue point" of repackaging was shifted, consistent with a slowing of θ oscillations and reflecting more generally age-related changes in cortical oscillations.

Investigating emotional word comprehension, Ku, Allen, and Lai (2022) instructed old and younger adults to read positive/negative and high/low-arousing words and pseudowords, and had these groups make word/nonword judgments. Older adults showed increased N400 signatures and left frontal α decreases (300–450 ms) for low-arousing positive compared to low-arousing negative words. This points to the existence of an arousal-dependent positivity bias during lexical retrieval. In addition, older adults exhibited a larger mid-frontal θ increase (500–700 ms) than younger adults for low-arousing negative words. This may point to a down-regulation of the negative meanings of low-arousing words. As such, the interface of lexico-semantics with language-external interpretation and emotional centers is impacted by age.

In the domain of speech comprehension, neural entrainment to the speech envelope is relevant to language comprehension (Ding, Melloni, Zhang, Tian, & Poeppel, 2016), whereby brain-to-speech coupling at low frequencies is connected to speech segmentation (i.e., inferences about phonemes, syllables, words, and phrases). In older adults, higher entrainment has been linked to improved language comprehension (Decruy, Vanthornhout, & Francart, 2019), with older adults showing the highest entrainment to the speech envelope. Older adults also display stronger cortical-tracking of lexical-level features than young adults under adverse listening conditions, even though comprehension scores among older adults are higher (Mesik, Ray, & Wojtczak, 2021), suggesting a complex interplay of entrainment mechanisms and differing (top-down vs. bottom-up) processing strategies.

The P600 ERP component, sensitive to syntactic violations (and not simply demands to verbal working memory; Gunter, Vos, & Friederici, 2002), presents as less asymmetric and more frontal in older adults (Leckey & Federmeier, 2017), pointing to age-related changes in the neural basis of syntactic processing. Age differences in the α band have been documented during sentence encoding (Beese, Vassileiou, Friederici, & Meyer, 2019). During a sentence comprehension task, Beese et al. (2019) found an age-related inversion in α, from a relative decrease in correctly remembered relative to later-not-remembered sentences in young adults, to an increase in correctly remembered relative to later-not-remembered sentences in older adults. Even though age does not appear to impact sensitivity to syntactic ambiguity, the gray matter integrity of the frontotemporal syntax network decreases with age, as does network connectivity, while general interhemispheric connectivity increases, which may reflect compensatory activity or diffuse activity as a result of reduced efficiency (Shafto & Tyler, 2014).

Low-frequency θ oscillations have also been shown to dissociate a language-specific from a domain-general processing mechanism across age groups. Beese, Meyer, Vassileiou, and Friederici (2017) showed that declines in sentence comprehension due to aging are related to changes in resting-state θ power within domain-general brain networks (central scalp EEG sites), while low resting-state θ power within the left frontotemporal language network predicts intact sentence comprehension. These two resting-state θ networks are also functionally decoupled relative to their independent internal coupling. As such, both young and older adults seem to utilize the same language network for basic comprehension, but declines in working memory-intensive sentence comprehension over the life span are likely due to changes within the association network subserving domain-general supplementary cognitive functions.

Exploring the neural signatures of elementary syntactic binding in young adults and older adults, Poulisse, Wheeldon, Limachya, Mazaheri, and Segaert (2020) found that syntax is associated with a qualitatively and quantitatively different neural signature in older adults; namely, a smaller increase in θ and α power for binding over nonbinding trials, whereas younger adults showed the opposite pattern. The authors suggest that these differences may be related to an increased reliance on semantic processing with increasing age. What has not yet been explored, to my knowledge, is whether interactional dynamics or some form of low-frequency neural code involving coupling and cross-band synchronization is also impacted by aging during basic syntactic processing (Murphy, 2025a). Even though distinct functional activity patterns in older adults are often interpreted as being compensatory (Cabeza, Anderson, Locantore, & McIntosh, 2002; see also Missonnier et al., 2011)—relatedly, older adults recruit additional brain regions compared to young adults during syntactic processing (Grossman et al., 2002; Shafto & Tyler, 2014)—this domain of research potentially brings with it implications for models of the neural basis of syntax (Murphy, 2025a), in particular given that Poulisse et al. (2020) found no evidence of an association between behavioral performance on their syntax task and the neural signatures of binding in older adults. The more general consensus in the field is that although certain components of network dynamics change with age, "there is no consistent evidence that core language processes are underpinned by different neural networks in younger and older adults" (Shafto & Tyler, 2014: 583). Nevertheless, other recent work by Markiewicz, Segaert, and Mazaheri (2021) using EEG reveals that young adults elicit an early semantic binding signature (around the onset of target word presentation in two-word phrases) via a smaller low-β increase during semantic binding (vs. no binding). Healthy older adults display a semantic binding signature around 500 ms later, via a smaller β decrease during semantic binding.

Using MEG, Bertels et al. (2023) characterized the neuromaturational basis of speech processing in noisy environments by quantifying how cortical oscillations (in participants aged 5–27) track linguistic structures in connected speech. The extraction of prosodic cues and their maintenance during a noisy, multi-talker background matured up to age 9, and continued to mature over age. Neuromaturational milestones were also reached later for linguistic units of decreasing size, and additional neuromaturational milestones need to be reached for processing to be optimal in adverse noise conditions.

5. Conclusion

There appears to be a broad range of neural indices of age-related changes in language processing. A challenge for future research is to relate, on a fine temporal scale, some of these indices to language-external age-related changes, such as in the neural basis of attention and working memory. The breakdown in the brain rhythms of language may bring with it consequences for aspects of inter-areal synchronization and communication, or forms of conceptual cross-modal integration and composition that language use readily facilitates—a topic of considerable significance to the diagnosis and treatment of age-related cognitive decline.

Conflict of interest

The author declares no conflict of interest.

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Appendix

Glossary of Terms

Bottom-up/Top-down processing: The use of lower-level, perceptual processing (bottom) versus the use of existing, prior knowledge and representations to derive inferences.

Cell assembly: A network of functionally connected neurons that is activated by a particular mental process and whose excitatory connections have been strengthened in time.

Cross-frequency coupling: When interactions between discrete frequency bands give rise to more complex regulatory structures. For instance, phase-amplitude coupling denotes the statistical dependence between the phase of a low-frequency band and the amplitude of a high-frequency band.

Embedding: The ability for a linguistic unit to host within it another linguistic unit.

Generative grammar: The branch of linguistics which assumes that natural language is a mental computational system of rules generating an unbounded array of hierarchically structured expressions, with varying degrees of acceptability.

MERGE: The computational operation that is commutative and non-associative which selects two objects from the lexicon, α and β, and forms an unordered object mapping them to an active workspace, $\mathrm{WS} = \{\alpha,\beta\}$.

Oscillation: The unfolding of repeated events in terms of frequency. In the context of the brain, neural oscillations (or brain rhythms) are repetitive patterns of activity caused by excitatory and inhibitory cycles in cell assemblies.

Phase-locking/synchronization: When multiple cyclic signals oscillate such that their phase angles stand in a systematic relation.

Phonology: The system of sound, or a set of sound-related features and rules stipulating how these features interact in a given language.

Recursion: The hallmark of natural language syntax; when a linguistic rule can be applied to the result of the application of the same rule, creating, for instance, "nested" structures like "John, who likes Sarah, will come to the party" from "John will come to the party."

Syntax: Informally termed the "grammar," this is the set of principles governing the structure of morphologically complex word-like elements, phrases and sentences, and their combinatorial processes.

Traveling waves: Oscillations which migrate in phase coherence across the brain, whereby the spiking of neural clusters is coordinated not just across two fixed points but across a particular extended path.