Psychological Research (2025) 89:151
https://doi.org/10.1007/s00426-025-02173-6

REVIEW

Evidence of Embodiment-based changes in older Adult Language

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Received: 10 October 2024 / Accepted: 11 August 2025

Abstract

It is increasingly recognized that the embodiment of older adults reflects the declines in physical capacity that typically attend aging. Specifically, older adult embodiment is characterized by decreased involvement of bodily and action-system inputs, true for both cognitive and perceptual processing (Costello & Bloesch, *Frontiers in Psychology,* 267, 2017; Kuehn et al., *Neuroscience & Biobehavioral Reviews*, 86, 207–225, 2018), and for emotional processing (Mendes, *Neuroscience & Biobehavioral Reviews*, *86*, 207–225, 2010; MacCormack et al., *Emotion Review*, *9*(1), 36–45, 2024). However, it is unclear whether this "less embodied" effect extends into language capacity, for language is relatively well preserved in healthy aging with no obvious manifestations of embodiment-based changes. This critical review paper explores the question through evidence drawn from multiple facets of language processing that are pertinent to the embodiment of language. We find positive evidence of embodiment-based reweighting (EBR) effects for older adult language, with decreased salience of physicality and action-based inputs that are offset by increased weighting for visuo-cognitive facets of language. We interpret the EBR model in light of both compensatory and predictive coding models, and discuss its broader significance and consequences.

Embodiment theory argues that language and concepts are ultimately grounded in our physicality, be that our physiological needs and goals or our ability to move and interact with the world (Glenberg, 2010). Yet what happens to language processing when the body's nerves, muscles, organs, and systems eventually begin to deteriorate with advanced age? This critical review paper seeks to answer this question. Specifically, we document a common pattern across several aspects of language in which older adult language is less directly affected by body- and action-based factors, and more directed by visual and cognitive factors. We name this the *Embodiment-Based Reweighting* (EBR) effect in language and argue that it reflects two dynamics: (1) the age-related deterioration of the physiological and motor-action systems, and (2) the compensatory reweighting of neural signals to optimize older adult language semantics and performance. A schematic of our overall model is presented in Fig. 1, with details on this model to follow. The EBR effect has been previously unexplored in the embodied and grounded language literature, and it holds both practical importance for the linguistic and gerontological sciences as well as theoretical importance for embodiment theories.

Our theoretical presupposition is that language is embodied and grounded in the sensorimotor system. This perspective began establishing itself in the late 1990s, thanks to influential work on concept formation (i.e., Barsalou, 1999) and the syntax and grammar systems (Pulvermüller & Fadiga, 2010). It is now generally accepted that language is constrained by the motor-action system (see Dove, 2023; Fischer & Zwaan, 2008; Zwaan, 2014). To our knowledge, an age-related shift in the embodiment of language has never been directly addressed, and the answer is not self-evident, for language is largely preserved in older adulthood, and there are no obvious manifestations of such changes. We posit that the many interrelated yet gradual processes that underpin

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Published online: 30 September 2025

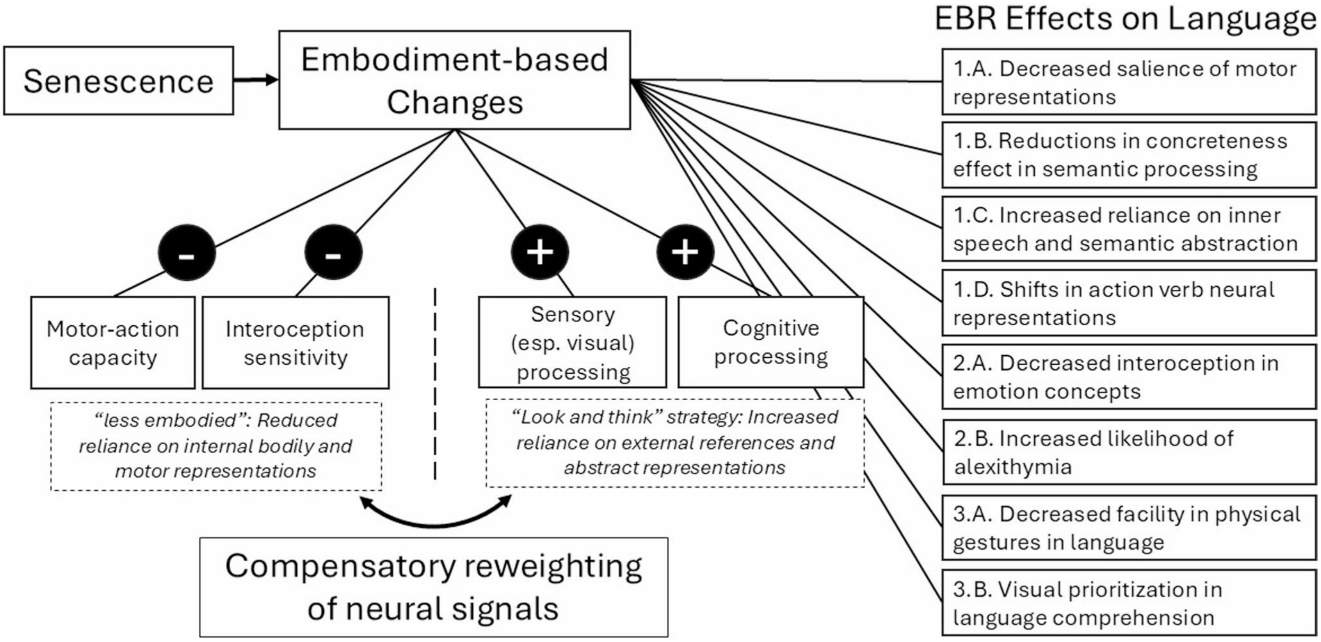

Fig. 1 The EBR Model of Older Adult Language. Caption. Senescence (i.e., biological aging) produces a wide range of physical and mental changes that result in an embodiment equilibrium that is qualitatively different from that of younger adults. Embodiment changes in senescence are characterized by decreases in physical actions and physiological signals that ultimately degraded internal motor representations and body interoception (i.e., a "less embodied" status). Compensatory mechanisms include both increased sensory (especially visual) reliance and increased weighting towards overtly cognitive and abstract processing, resulting in a characteristic "look and think" strategy. The effect on language is multifaceted, with EBR effects expressed in semantic knowledge (Part 1), emotional language processing (Part 2) and conversation strategies (Part 3)

biological aging (i.e., senescence) should alter the embodiment of older adult language (López-Otín et al., 2013).[1] Senescence is here defined as the gradual deterioration of the physical functions in aging, in contrast to *chronological* aging, or the mere passage of life years. Physical declines in senescence are both obvious and well-established (for reviews, see Fried et al., 1994; Rejeski & Mihalko, 2001), including decreases in muscle mass, strength (Roubenoff & Castaneda, 2001), motor coordination (Patel et al., 2014), energy and activity levels (Tinetti, 1986), balance control (Laughton et al., 2003), and slower motor responsiveness (Falkenstein et al., 2006). Such physical changes culminate in broad motor-action declines, including fine motor tasks (Krampe, 2002), postural control performance (Lacour et al., 2008), and motor learning (i.e., overt or implicit pickup of motor sequences) (Seidler, 2007). Similarly, perceptual declines are also common in older adulthood. These include both the exteroceptive systems such as the visual (Andersen, 2012) and auditory systems (Howarth & Shone, 2006), yet also interoception of interior physiological sensations, e.g., awareness of cardiac, respiratory, and gastric signals (e.g., Khalsa et al., 2009; MacCormack et al., 2021; Mikkelsen et al., 2019; Raimo et al., 2021).

[1] Importantly, the age at which senescence begins after physical maturation varies by individual. A person's so-called "biological age" may not match their chronological age, due to environmental factors (e.g., socioeconomic status, pollution) and individual factors (e.g., lifestyle, epigenetics) that may accelerate or decelerate the processes of senescence (Levine,2013).

Age-related decline of embodiment functions

Experimental and theoretical work in gerontology has increasingly focused on how such changes alter the embodiment of older adults (Mille et al., 2021; Naughton, 2022; Vallet, 2015). Mendes (2010) was one of the earliest theorists to outline the implications of age-related shifts in embodiment. She argued that in late life aging, awareness of bodily states decreases alongside poorer perception of internal physiological changes (i.e., *interoception*) and motor positions and movement (i.e., *proprioception*). She described this shift in more muted bodily signals as *maturational dualism*, in which the loss of coherent interoceptive, somatosensory, and motor-action inputs (whether through decreased signal output or increasingly noisy signals) leads to downstream effects on the mind and behavior. In turn, older adults' muted inner-body responsiveness should presumably produce a compensatory increase in reliance on the external world as a direct reference point for their behavioral response.

Kuehn et al. (2018) similarly argued that embodiment alters with aging. Their NFL model described embodiment-based changes in aging operating simultaneously at three levels: declines at the neuronal (N) level (such as increased neuronal noise and inefficient neuronal communication) feed into functional (F) consequences such as impaired spatial perception and motor responses, which result in restrictions of daily-life (L) activities. Senescence, in other words, includes degradation of the neural signals that allow for vibrant internal mental representations, with downstream effects on purposeful actions. Efficient actions require an integration of overt physical prowess (e.g., moving limbs, vestibular control, etc.) with internal mental mapping of the action. For older adults, the resulting internal action models are degraded and do not allow for accurate prediction of the action's trajectory. Lacking these internal guideposts, older adults adopt a different strategy for performance success, relying more on direct visual perception of the world as an external reference (Diersch et al., 2013, 2016). Thus, the decline of physicality results in a compensatory shift that is more reliable and efficient for older adults, albeit both slower and more effortful.

Compensatory adjustments

The decline of bodily capabilities in aging, in other words, is not the end of the story. Embodiment is dynamic and flexible, and performance can be optimized through adjustments at both the neural and behavioral levels. Deterioration or loss of input signals from one sector may necessitate an increase in processing in another. Thus, the embodiment equilibrium necessary for optimized performance is flexibly adaptive to declines in select nodal units. This flexible adaptation of the embodiment equilibrium is an example of neuroplasticity, defined as the changes to the neural network based on either internal (i.e., body-based) or external factors that gather across the lifetime (Trojan & Pokorny, 1999). Connectivity within the neural network gradually adjusts in connection strength (either strengthened or weakened) based on signal errors (e.g., through Hebbian learning) to stabilize into optimal performance.

Costello and Bloesch (2017) argued that neural compensation was a direct response to embodiment-based declines in aging. They articulated a two-fold thesis. First, older adults are "less embodied", meaning that aging results in decreases not merely in the overt mechanics of physical action but also in the internal mental models required for efficient action. This position is broadly consistent with both Mendes (2010) and Kuehn et al. (2018). Second, these embodiment-based declines were compensated through increased reliance on visual and cognitive processing, compensatory adjustments that are subtly expressed as they reflect a lifespan decline in physicality markers. At the neural level, compensation is expressed in a down-weighting of physical and motor signals and a compensatory upweighting of visual processing. At the behavioral level, older adults rely more upon visual processing over both body-based and action-based inputs such as motility, kinesthetic, proprioceptive, tactile, and other action-system factors. Costello and Bloesch (2017) documented numerous examples of visual prioritization, including multisensory integration (Diaconescu et al., 2013), visuo-motor control (Heuer & Hegele, 2014; Rand & Heuer, 2013; Toledo & Barela, 2014), and in action-prediction (Diersch et al., 2016; Sacheli et al., 2023).

More recently, Costello & Bloesch (2021) have argued that this embodiment-related decline of internal representations necessitates a more direct engagement with the external world. In contrast to younger adults, whose motor representations are imbued with physicality markers that allow for quick and efficient actions, older adults operate with mental representations that are somewhat 'physicality depleted', and consequently their internal action models are less likely to be calibrated for successful performance. The embodiment of older adults, in other words, is qualitatively different from that of younger adulthood - less driven by bodily immediacy and directed more towards the external world. This translates into an 'exteriority bias', in which the visible world serves as an external anchor for thought and action. The result is a far more reliable mode of engagement for seniors, although performance is characteristically slower, more cautious, and less emotionally valenced - a *look-and-think* response set rather than the more body-infused immediacy of youthful embodiment.

Caveats and qualifiers

This "less embodied" thesis requires three important qualifiers. First, we are not arguing that older adults are *disembodied*, which would be impossible under the embodiment theory approach. Like everyone, older adult minds are still embodied. Rather, "less embodied" refers to the reweighting of neural signals as a compensatory response to the effects of senescence on motor and physiological functions. In this regard, the altered embodiment in aging is better referred to as age-related *changes to*, rather than *declines in*, embodiment. To avoid the confusion that the phrase "less embodied" may generate, for this paper we will use the phrase "embodiment-based reweighting", or the *EBR effect*, to describe this characteristic downweighting of physicality markers and upweighting of visuo-cognitive processing.

Second, we argue that the increase in visual processing is often tantamount to increased cognitive processing for two primary reasons. First, most experimental settings feature visual inputs, such as stimuli presented on a computer screen, or words and pictures presented on paper. In such settings, seeing is often tantamount to gathering information within a visually-rich testing environment (e.g., the use of fixation time as a proxy for cognition in looking-measure paradigms). Such testing settings can be especially challenging for older adults, whose cognitive and perceptual declines (especially for vision and audition) have a reciprocal relationship (Roberts and Allen, 2016). Additionally, vision, more than any other sense, provides detailed information to alert subjects of relevant changes in the field, and thus often serves as the primary means to bias responses. The intimate link between sight and knowledge has been coined *visual dominance*, a phenomenon explored in both psychology (Posner et al., 1976) and philosophy (Jonas, 1954). Understood in this regard, the visual dominance in older adults as discussed in Costello and Bloesch (2017) is an intensification of a trend latent across all age groups, for it reflects the raw potential of the sensory modality itself. As the body ages, the somatosensory and sensorimotor systems decrease in efficiency, resulting in increased reliance on its most information-rich sensory modality: vision[2].

Finally, these distinctions between "embodied" vs. "cognitive" dimensions of language are not meant to reify mind-body dualism, nor to contradict the principles of embodied cognition. Instead, these terms are used to describe the interplay of embodied, sensory-driven processes and more abstract, prediction-driven processes. "Increased cognitive processing" should be understood as greater reliance on higher-order and abstract processing of more distilled or extracted representations that summarize across a lifetime of embodied instances. Indeed, as we describe below, older adults are less reliant on motor-action immediacy when using language, and more reliant on deliberative (and visual-based) strategies, on a lifetime of crystallized intelligence and knowledge, on mental simulations, and other elements that we detail herein.

Language in late life

Do EBR effects influence older adult language? The aforementioned research on older adult embodiment was largely directed towards motor-action responses, and not to language capacity. In fact, it is not at all clear that language would be affected. After all, language is one of the few cognitive abilities that is relatively preserved in older adulthood. Both language comprehension and vocabulary knowledge hold steady or even increase in advanced age (Burke & Shafto, 2011; Stamatakis et al., 2011; Tyler et al., 2010; Wingfield & Grossman, 2006). For instance, Kavé and Halamish (2015) found that older adults outperformed and were more confident than younger and middle-aged adults in vocabulary knowledge. Adjusting for processing speed declines, older adults can retrieve the meaning of words with high accuracy (Verhaeghen, 2003). Additionally, crystallized IQ, which generally reflects both productive and receptive language, holds steady in older adulthood (Kaufman & Horn, 1996; Rabbitt & Abson, 1991). In short, language comprehension is largely spared from negative aging effects when we factor out general age-related cognitive declines that may be needed for good comprehension.

A similar positive story arises for language production. Although both longitudinal and cross-sectional evidence find that older adults perform worse in producing or recalling language during lexical retrieval tasks (e.g., Barresi et al., 2000; Kemper et al., 2001; Taler et al., 2020; Verhaegen & Poncelet, 2013), these declines likely reflect broader cognitive declines that are not necessarily language-specific deficits (Salthouse, 2010). For instance, although word search and retrieval ability worsen with age (Albert et al., 1988; Wierenga et al., 2008), these failures are centered in broader declines in executive function rather than semantic knowledge. Age-related lexical retrieval slowdowns have also been shown to reflect declines in processing speed and inhibitory control (Barresi et al., 2000; Brink & McDowd, 1999; Cotelli et al., 2012) rather than language per se. Memory issues also explain the tip-of-the-tongue language failures common in older adulthood, in which the speaker "knows" the target word yet cannot extract it (Huijbers et al., 2017). Similarly, age-related slowing in verbal recall and verbal working memory likely are often attributed to the processing speed declines common to older adulthood (Kemper et al., 2001; Weaver Cargin et al., 2007). In total, language ability is largely preserved in healthy older adults after accounting for broader domain-general cognitive declines (Shafto & Tyler, 2014).

Evidence for EBR effects in older adult language

In what follows, we present evidence that confirms EBR effects in older adult language, with the evidence organized into three sections. In Part 1, we focus on EBR effects that alter semantic understanding, with these effects derived

[2] Note that there is nothing 'magical' about vision, and the truth of visual prioritization does not preclude the possibility that older adults may rely on the other sensory modalities for compensatory gain. However, most experiments feature visual stimuli, and visual information is generally regarded as providing the most detailed information about the environment. The primacy of visual perception is perhaps most clearly evident at the cortical level, as the primate brain devotes far more cortical space to visual processing than to the other sensory modalities (Zeki, 1993).

centrally from age-related declines in motor imagery. In Part 2, we document further semantic-level changes, but this time Related to age-related declines in interoception of physiological signals in emotions. In Part 3, we focus on EBR effects at the overt level of language performance, specifically on gesture use and multisensory components in conversation.

Part 1: the role of motor imagery in semantic understanding

Motor imagery declines in older adulthood

Embodiment theorists have long argued that language and concepts involve simulations, i.e., reenactments of sensorimotor experiences with objects, entities, and other people, helpful to prepare for action (Barsalou, 1999; Gallese, 2009). Motor imagery is an essential component to language processing, especially in conjunction with action-based language that elicits motor strip neural activation (Jeannerod, 1994, 2001). For instance, when we say or hear the word “running,” motor strip activations increase as we envision the image of a running person, as motor imagery and overt motor executions operate along overlapping premotor-parietal cortical areas (Hardwick et al., 2018). Language processing depends upon our capacity to simulate motor actions, especially for concrete and action-based language (O’Shea & Moran, 2017), but also more subtly in abstract language (Banks & Connell, 2023).

However, older adults struggle to generate motor imagery (Saimpont et al., 2013), a capacity that is crucial for accomplishing intentional actions, as motor imagery serves as an initial internal simulation that helps fine tune subsequent overt motor action (Wolpert & Kawato, 1998). For instance, Gabbard et al. (2011) found that younger adults (M_{age} = 20 years) performed significantly better in motor imagery tasks than older adults (M_{age} = 77 years) when estimating whether or not an object would be within reach for them to grasp. Several studies have confirmed this age-related decrement in motor imagery (Mulder et al., 2007; Personnier et al., 2010; Saimpont et al., 2013).

As consistent with embodied simulation theory (Barsalou, 1999), there is a strong correlative link between physical declines in aging and consequent motor imagery failures. Older adults with poor motor execution in a basic Timed Up and Go task tended to overestimate the time needed for task performance indicative of degraded motor imagery (Sakurai et al., 2021). Falling is a justified fear among seniors (Jung, 2008), one that is directly linked to motor imagery declines (Grenier et al.,2018; Sakurai et al., 2021). When performing in especially challenging physical tasks, older adults struggle to summon appropriate motor images to correct their online movements (Wang, Zhang, & Wilmut, 2025). This link between physical decline and motor imagery decline is correlative, and the direction arrow can also be flipped – improving motor imagery in seniors can assist in their physical actions (Saimpont, Metais, & Collet, 2023). A systematic review of the literature found that training sessions designed to improve motor imagery can lead to benefits in multiple physical tests, such as measures of balance control, gait speed, and Timed Up and Go (Nicholson, Watts, Chani, & Keogh, 2019). Indeed, a more recent review found that such gains were more strongly registered among older adults than for younger adults (Liu et al., 2023), although a recent randomized control trial found no evidence of improvement in walking performance (Nicholson, Steele & Wilson, 2025).

Reduced sensitivity for motor imagery produces downstream changes to motor semantics. Miklashevsky and colleagues (2024) used 2174 words (from Lynott et al., 2019) that differed in motor-relatedness and tested younger and older adults in two tasks: a lexical decision task and a reading task. They found that younger adults outperformed older ones in speed and accuracy in the lexical decision task with high motor-related words, while older adults’ performance was not affected by motor-relatedness. No difference was present between the two groups in the reading task, where access to semantics is minimal. These results highlight, with a large and controlled body of words, that motor semantics is influenced by aging. A complimentary finding is evident when word stimuli are rated along two embodiment dimensions: (1) perceptual strength (PS), a measure of the extent to which the words can be experienced by separate sensory modalities, and (2) body-object interaction (BOI), which measures the ease with which the body can physically express the word’s meaning (Lynott et al., 2019; Tillotson et al., 2008). When younger and older adults were tested, a characteristic pattern emerged of age group equivalence for most PS modalities and significant age-related BOI decreases (Miceli et al., 2022). Consistent with our hypothesis, motor semantics appears diminished by aging, likely due to reduced embodiment, while no strong effect is found in perceptual processing.

Concrete words: age-related reductions in the concreteness effect

The age effect on motor imagery is also manifest in the distinction between concrete and abstract concepts and words (review in Borghi et al., 2017), one of the key dynamics in the embodiment of language. Concrete words (e.g., “grasp”, “bottle”) have a more obvious embodied grounding, but even abstract words (e.g., “freedom”) evoke sensorimotor and interoceptive experience (Banks & Connell, 2023; Connell et al., 2018; Harpaintner, 2021; Mazzuca et al., 2021; Villani et al., 2019, 2021). Nevertheless, the relative weight of embodied factors varies between abstract and concrete concepts, as well as within sub-kinds of abstract and concrete concepts (Conca et al., 2021). For abstract concepts, language and social interaction are crucial to help form categories based on sparse sensory inputs. For concrete concepts, which more directly reflect perceptually similar exemplars, sensorimotor experience is more critical. At the same time, different embodied components can have different weight depending on the kind of concrete or abstract concepts: for example, interoception is particularly crucial for representing emotional abstract concepts (Connell et al., 2018; Villani et al., 2021; Winter, 2023), but not for spatio-temporal and numerical abstract concepts (Villani et al., 2019). The more immediate grounding of concrete concepts may help explain why they are learned earlier (Gleitman et al., 2005; Bellagamba et al., 2022), processed faster, and recalled better than abstract concepts (Paivio, 1990). This advantage of concrete over abstract concepts in semantic processing and memory recall is called the *concreteness effect* and has proven to be a reliable result across studies in children and younger adults.

How does aging affect the concreteness effect? A critical finding, documented by multiple studies, is a decrease or even an inverse of the concreteness effect in older adults (see reviews in Borghi & Setti, 2017; Pezzuti et al., 2021). The reduction of the concreteness effect is particularly striking because a key principle in linguistic aging is "first in, last out"; i.e., the earlier you learn words, the later you forget them (Hodgson & Ellis, 1998). Abstract words and concepts are typically acquired later than concrete concepts. Furthermore, word frequency and age of acquisition are generally correlated, such that the later acquired and less frequently used words decay earlier than the early acquired and more frequently used words (Jefferies et al., 2009). Thus, because concrete words are learned earlier than abstract words, the concreteness effect should be increased in advanced age – yet, surprisingly, it is reduced.

Furthermore, the available evidence largely points to the surprising resilience of abstract concepts for older adults. For instance, Peters and Daum (2008) asked younger adults (M_{age} = 21 years), middle-aged adults (M_{age} = 42 years) and older adults (M_{age} = 61 years) to rate the pleasantness of words and respond differently depending on whether they recalled emotions associated with the word (recollection) or whether they simply remembered the word. Although overall recollection declined with age, with abstract words, no decline occurred from mid-to-late age, evidencing a reduced concreteness effect. Tournier and Postal (2011) confirmed that the concreteness effect is less marked with age. They investigated strategies used by younger (M_{age} = 20.68 years) and older adults (M_{age} = 68.46 years) in a paired-associate word task. Participants had to memorize visually displayed pairs of concrete, middle, and abstract words, choosing among three strategies: imagery (linking words with images), sentence (linking words within the same sentence), or repetition. Crucially, older adults chose to use the imagery strategy less, which penalized them, especially in concrete word pair trials. Overall, older adults were efficient but markedly rigid in their selection strategies, relying less on imagery and more on sentence strategies. These results are consistent with earlier evidence of an age-related reduction in the concreteness effect when imagery strategies are necessary for effective performance (Dirkx & Craik, 1992; Rissenberg & Glanzer, 1987). Huang et al. (2012) found similar concreteness effects between younger and older adults at the lexical level, yet at the compositional level (i.e., with noun-adjective combinations), no concreteness effect occurred in older adults. The authors interpreted this difference as older adults being less able to elicit imagery spontaneously, supporting the contention that the EBR effect is driven in part by reductions in motor imagery. More crucially, the reduction of the concreteness effect appears to be driven by a decline in the processing of concrete words, with no corresponding decline in the processing of abstract words. Because linguistic experience is more critical for representing abstract concepts, this process highlights the importance of language in compensating for the reduction of embodiment that occurs during aging, in line with the EBR model.

Abstract words and the inner speech strategy

The previous section suggests a causal pathway: age-related sensorimotor processing declines contribute to motor imagery declines, ultimately yielding reductions in the concreteness advantage. However, this EBR effect may be offset by a compensatory reliance on inner speech, the interiorized, self-directed dialogue that can facilitate thought (Alderson-Day & Fernyhough, 2015). According to a recent proposal, inner speech might be especially critical during abstract concept processing, both because it facilitates the inner search for meaning and because it helps people retrieve and re-explain to themselves the word's meaning (Borghi & Fernyhough, 2023; Fernyhough & Borghi, 2023). This continued reliance on inner speech represents greater reliance on language (as opposed to the extra-language immediacy of sensorimotor response) and is thus consistent with increased cognitive processing in seniors, a result expected given our EBR proposal.

There is some evidence consistent with this latter interpretation. Roxbury et al. (2016) used an acoustic, lexical decision task involving concrete, abstract, and pseudowords conducted with younger (M_{age} = 27.35 years) and older (M_{age} = 71 years) adults. Behavioral results showed faster responses for concrete than abstract words (i.e., the concreteness effect) in both age groups, yet fMRI analyses revealed differences between the underlying neural mechanisms. When older adults were processing abstract concepts, there were selective increases in the left inferior frontal gyrus (IFG), an area that is involved in working memory maintenance, sub-articulatory processes, and inner speech (Binder et al., 2011). It is possible that the compensation reflects more working memory and phonological processes associated with left IFG than semantic ones, because the same effect occurs with abstract words and pseudowords. Consistent with this interpretation, younger adults engage more the left angular gyrus (AG), supporting semantic processing. Older adults also use left AG, but not more frequently for abstract than concrete concepts, suggesting a greater need for integration and compensation in phonology than in semantics.

Overall, the abstract vs. concrete distinction reveals two major findings that are consistent with the EBR proposal. First, older adults exhibit a reduction in the concreteness effect that is common in younger language users. Second, the research suggests the existence of two mechanisms that might act simultaneously: (1) a reduced capability to process sensorimotor information, influencing in particular concrete concepts, and (2) cognitive compensation in the form of increased use of language, either overt or inner speech, contributing to the resilience of abstract concepts.

Action verb processing and the mirror neuron system (MNS)

Action verbs are an especially important test case of the embodiment of language, as the processing of action verbs elicits comparable cortical activations as the motor-action system itself (Bidet-Ildei & Toussaint, 2015; Boulenger et al., 2006; Pulvermüller, 2005). This shared neural substrate is often characterized as the mirror neuron system (MNS), a cortical network whose neurons are jointly activated for actions performed by oneself and for observation of similar actions performed by others (Bonini et al., 2022; Lago-Rodriquez et al., 2013; Rizzolatti, 2005). The classical MNS regions in humans involve a series of fronto-parietal areas, including primary motor cortex (M1), premotor cortex (especially inferior frontal gyrus (IFG), and inferior parietal lobule (IPL) (for recent review, see Heyes & Catmur, 2022). The MNS-language link is grounded in embodiment, as current theory argues that language evolved from imitation of gestural communication (Rizzolatti & Craighero, 2004; Tettamanti et al., 2005).

Is the mirror neuron system intact in older adults? The evidence from three fMRI imaging studies suggests it is. Farina et al. (2017) explored MNS activity with healthy older adults (M_{age} = 73.8 years) (as well as MCI and AD older adults) in a task in which participants either observed actions performed by others or viewed objects presented for participant manipulation. Healthy older adults activated the classic MNS network. However, this study offered no younger adult contrast, and therefore it is impossible to statistically determine potential age-related activity differences. Nedelko et al. (2010) assessed MNS activations with both younger (M_{age} = 26.2 years) and older (M_{age} = 63.0 years) adults in an action observation and action imagery task sequence. Although they found an age-related increase in overall brain activations, the functional activations for the MNS system itself yielded no age group differences. Note that this age group equivalence for the MNS may reflect the fact that this experiment did not require actual motor actions, but rather simply observing manipulable objects. The EBR effect would predict that age-related decreases in motor efficiency (rather than the more resilient visual domain) may be more likely to alter brain efficiency. This possibility was confirmed in Di Tella et al. (2021), who tested both younger (M_{age} = 26.7 years) and older (M_{age} = 71.5 years) adults in an fMRI task in which participants observed hand actions performed by others, and then executed comparable grasping hand movements. As expected, both younger and older adults activated the MNS system. Yet the older adults elicited greater bilateral activations in premotor and prefrontal regions, which the authors interpreted as greater deliberation during the motor-action sequences. In their apt words, "physiological aging is associated with the necessity to recombine simple motor acts *de novo* each time" (p.7). This observation is entirely consistent with the EBR thesis of (1) reduced automaticity of ideomotor actions, and (2) compensatory increases in visuo-cognitive processing.

To the best of our knowledge, no brain imaging study has directly tested potential aging effects in the MNS and language relationship. However, Bidet-Ildei and colleagues (2020) conducted a behavioral experiment that assessed age-related declines in the action-language Relationship based on the physical declines of older adults. In their experiment, 25 younger adults (M_{age} = 20.9 years) and 20 older adults (M_{age} = 74.1 years) performed a priming task in which participants heard an action word and then were shown simple line drawings under three possible conditions: congruent (e.g., the word "dance" followed by an image of a dancer), incongruent (e.g., the word "dance" followed by an image of a swimmer), and unrelated (e.g., the word "dance" followed by an image of a light bulb). Participants were instructed to report through keystrokes whether the presented images featured a person or not. Previous work had shown that the congruency condition improved task performance (Bidet-Ildei et al., 2011). For younger adults, the results confirmed the expected effect that congruent trials were correctly identified more quickly than incongruent trials. Yet for older adults, there was no significant congruency effect, which the authors attributed to the difficulty in utilizing motor imagery representations in the task.

The Bidet-Ildei et al. (2020a, b) study was behavioral in design, and therefore limited in terms of identifying specific neural causal factors. More recent work has found that when older adults attempt to predict action sequences, they employ a visual processing strategy (driven by occipital-temporal brain regions) rather than with a motorically-based strategy (driven by fronto-parietal brain regions) (Sacheli et al., 2023). Although this study did not pertain directly to language processing, it confirms earlier reports that age-related declines in the salience of sensorimotor inputs lead to the failure of the internal models of action sequences that younger adults readily employ (Zapparoli et al., 2013, 2016). Taken together, these intriguing findings are consistent with the EBR proposal of a disconnect between sensorimotor action and older adult language.

Part 2: semantic changes in emotional Language based on interoceptive declines

Language is frequently emotional and can serve as a vehicle for communicating and understanding emotions (Lakoff, 2016; Lindquist, 2017). But language also helps constitute emotion concepts—or the semantic categories we use to organize, abstract across, understand, and make meaning of richly varied emotion percepts and experiences (Lindquist et al., 2015; Lindquist, Satpute, & Gendron, Lindquist et al., 2015a, b; Lindquist, 2017). Consider, for instance, the phenomenon of semantic satiation, in which participants are asked to repeat a word (e.g., "anger") multiple times, resulting in a temporary impairment in the perception of that emotional facial expression (Lindquist et al., 2006). Similarly, learning words for a new emotion concept (e.g., feeling "glep") leads individuals to start perceiving that new emotion in novel facial muscle configurations (Doyle & Lindquist, 2018). Labeling an emotional state precisely ("frustrated") vs. generally ("bad") vs. not labeling also has divergent effects, fundamentally intensifying, altering, or reducing a given emotion and its related physiological changes as they unfold (Lindquist & Barrett, 2008; Kassam & Mendes, 2013; Nook et al., 2017a, b; Torre & Lieberman, 2018). Emotion words further provide an anchor around which semantic and episodic knowledge of emotion episodes can be acquired, organized, and complexified with age (Nook et al., 2017a, b).

Although language matters for emotion, what happens to the emotional content of language amidst age-related shifts in embodiment? This question remains largely unexplored. Here we highlight two areas of evidence: (1) shifts in the semantic representation of emotion, and (2) difficulty interpreting, describing, and identifying emotions (i.e., alexithymia).

Shifts in the semantic representation of emotion

Recall that in some embodied cognition accounts, "concepts" are argued to be multimodal simulations that re-enact prior experiences associated with the conceptual object (Barsalou, 1999; Gallese & Lakoff, 2005). Emotion concepts (e.g., *frustration*, *elation*, and *sorrow*) are particularly interesting from an embodied cognition perspective because while they are "abstract" relative to concrete objects and events, emotions bring together both sensory and cognitive elements. For example, emotions include many concomitants, including internal bodily changes (e.g., interoceptive sensations), nonverbal changes (e.g., motor reactions, facial expressions, posture), exteroceptive perceptions of situational events (e.g., seeing an attacker punch a victim, hearing a woman scream), alongside cognitive evaluations or appraisals of the meaning of these sensory modalities (e.g., an appraisal of harm, threat, belonging, support, etc.). As such, when people bring to mind the semantic category of "anger," this category is thought to include rich multimodal summaries or abstractions of both past embodied, situated sensory experiences during prior experiences of "anger" as well as more evaluative associations or functional meanings made about those sensory experiences (e.g., Del Cristaldi et al., 2024; Hoemann & Barrett, 2018; Lindquist et al., 2015a, b).

From an embodied cognition perspective, late life shifts in biological functioning—such as the aging of physiological or interoceptive and motor functions—should lead to shifts in the semantic representations of older adult emotions. Furthermore, this semantic shift in embodied representations of emotion should presumably reflect subjective or perceptual differences in how older adults experience their own emotions as less tied to interoceptive or physiological concomitants. On the other hand, older adult embodied cognition may leave intact or perhaps even compensate for these interoceptive declines by relying on their knowledge and experiences with the exteroceptive (e.g., visual, auditory) or situational appraisal features of emotion. Building on these hypotheses, the *physiological hypothesis of emotional aging* (MacCormack et al., 2020, 2021, 2024) argues that age-related changes in peripheral physiological functions, interoception of that physiology, and neural representations or regulation of physiology and interoception should serve as an important vehicle by which emotions can age, including the semantic meanings of how older adults understand a given emotion concept.

As a first test of differences in the embodied nature of older adults' semantic representations of emotions, MacCormack et al. (2021) adapted a classic property verification task drawn from embodied cognition research (Kan et al., 2003; Pecher et al., 2004) to assess whether older adults might have "less embodied" (specifically, interoceptive) associations for emotion concepts relative to younger adults. In this task, participants rated how much they associated a variety of negative emotions with three types of property modalities: interoceptive sensations (e.g., "heart racing") vs. nonverbal behaviors (e.g., "clenched fists") vs. propositional, situational appraisal features of emotion (e.g., "bad news"). Stimuli were matched on word length and lexical complexity and statistical models further controlled for age differences in reaction times to help limit confounds due to processing speeds. Data were collected from participants across adulthood (i.e., 18–72 years) to better approximate age as a continuous factor. Older adults were less likely to associate interoceptive properties with emotion concepts and somewhat less likely to associate nonverbal properties with emotion concepts than younger adults did. There were no age differences in associations with situational properties. Interestingly, age differences in interoceptive associations were particularly robust when considering high arousal emotions, such as anger and fear, which tend to involve greater physiological activation.

In a follow-up experience sampling study, participants (18–67 years) rated how much they experienced interoceptive sensations, nonverbal behaviors, and situational appraisals during daily life emotions—this time also including a matched number of positive emotions. Again, older adults were less likely to report experiencing interoceptive sensations during emotion episodes in daily life relative to younger and middle-aged adults, and this was especially true for high arousal emotions regardless of whether those were positive or negative emotions. Altogether, these results provide initial evidence that physical aging may result in both *experiential* and *conceptual* shifts in how older adults link the body to emotion in their semantic representations and self-reports.

Alexithymia in older adults

Despite improved emotional wellbeing in late life, older adults surprisingly tend to exhibit greater *alexithymia* or difficulty in describing and labeling their feelings (literally "no words for emotion" in Greek; Sifneos, 1973). Greater alexithymia in late life is an established finding (Correro et al., 2021; Henry et al., 2006; Mattila et al., 2006; Santorelli & Ready, 2015). Alexithymia is thought to encompass three components: (1) difficulties with describing one's feelings, (2) difficulties identifying one's feelings, and (3) the tendency to be externally-oriented at the expense of internal awareness (Nemiah, 1977; Taylor, 2004). Because alexithymia involves greater difficulty distinguishing between internal states (e.g., bodily sensations vs. emotional states), alexithymia is sometimes accompanied by the over-reporting of somatic complaints and health issues, including the "somatization" of emotional distress (De Gucht & Heiser, 2003; Lanzara et al., 2020; Lumley et al., 2007; Raffagnato et al., 2020). Indeed, growing research strongly implicates interoceptive impairments in alexithymia (Brewer et al., 2016; Herbert et al., 2011; Shah et al., 2016; Zamariola et al., 2019; see Trevisan et al., 2019 for meta-analysis). Thus, the increase in alexithymia in late life may be explained by the fact that older adults tend to experience both interoceptive declines and somatization increases (e.g., Hanssen et al., 2020; Khalsa et al., 2009; Van Driel et al., 2018).

Notably, although older adults can show increased difficulties in identifying and describing their emotions, the "externally-oriented" component of alexithymia is more prominent in older adults (e.g., Correro et al., 2021). The idea that older adults are more externally-oriented at the expense of their ability to be aware of their emotions and internal sensations provides convergent evidence aligned with other theories and findings discussed herein on older adult embodiment declines. In parallel to Costello and Bloesch (2017)'s findings on visuo-cognitive dominance, older adults' emotional processing may increasingly rely on situational, external cues (in turn tied to semantically-encoded concept schemas and propositional knowledge) rather than embodied cues drawn from interoceptive, proprioceptive, and other bodily sources.

Although this hypothesis remains underexamined, work on the effects of semantic dementia and aphasia on emotion (Lindquist et al., 2014; Souter et al., 2021) further suggests that access to language and emotion words are critical for categorizing more basic affective percepts into discrete emotional states of anger, disgust, fear, etc. More generally, this suggests that language helps encode, organize, and apply concept knowledge about emotions, transforming more ambiguous and diffuse "affective" impulses (i.e., subjective feelings of valence and arousal rooted in neurophysiological states) into distinct emotional states (Lindquist, MacCormack et al., 2015a; Lindquist, Satpute et al., 2015b). Thus, although older adults may be more likely to experience alexithymia and lower-level affective shifts in valence and arousal due to embodiment decrements, they may be able to maintain their overall degree of emotional functioning in part via their preserved concept knowledge and associated language ability (as proposed in MacCormack & Lindquist, 2017 and MacCormack et al., 2024). This late life preservation of semantic memory or knowledge may serve as a valuable compensatory resource for older adults' emotions amidst physical aging.

Part 3: overt language performance

In summary, EBR effects are evident in older adult semantic understanding due to changes in motor imagery (Part 1) and interoception of physiological signals of emotional reactions (Part 2). However, we argue that these EBR effects extend beyond mere 'interior' components in semantic understanding and indeed are evident at the more overt behavioral level of conversation, specifically in terms of gesture use and multisensory processing in conversation.

Gesture in late life language comprehension and production

We speak with both the mouth and the hands. Gesture use is an especially concrete manifestation of the embodiment of language, as gestures are physical actions used to assist and clarify meaning (Hostetter & Alibali, 2008). Interestingly, older adults show declines in producing and understanding gestures. Although older adults use comparable numbers of gestures relative to younger adults when speaking (Theocharopoulou et al., 2015), their gestures have differing qualities relative to younger speakers. Older adult gesturing is more focused on conveying spatial information (Özer et al., 2017) and less directed to direct representation (e.g., using double clenched fists to signify a fight) (Feyereisen & Havard, 1999). They also use significantly fewer iconic gestures than younger adults (Arslan, Ozer, & Goksun, 2023). Iconic gestures are directly representational, wherein the hand or arm directly represent the concrete or more complex notion being articulated (e.g., two hands cupped to the eyes to represent binoculars). Iconic gestures are especially important for skilled communication as they augment the semantic information provided by spoken words (Willems et al., 2007). In this manner, older adult gesture production is often not well tailored to listeners. Gesture use typically increases when the speaker knows that the listener has less knowledge on the topic and decreases when the speaker and listener have shared understanding of the subject matter. But older adults are less likely to adapt their gestures in this manner, as older adult gesturing is more "fixed" as a routinized action rather than fluidly adaptive towards the listener's needs (Schubotz, Ozyurek, and Holler, 2019). Importantly, gesture production in older adults has been linked to mental imagery scores (Arslan & Göksun, 2021), reiterating the central importance of age-related decreases in mental imagery on older adult language.

Older adults also show differences in gesture comprehension (i.e., "reading" the gestures of others), as if they have downgraded the informational value of bodily movements. Although they depend considerably on facial displays in conversation, older adults are less likely to attend to gesturing arms and hands (Cocks et al., 2011; Thompson, 1995). For example, when participants watched silent videos of emotional actors with the center of faces blurred (forcing attention solely to gross bodily displays), older adults misidentified emotional expressions than younger adults and were more likely to be confused by exaggerated or ambiguous nonverbal cues (Montepare et al., 1999). More recent data from Schubotz et al. (2021) confirmed this Result. They tested 28 younger (M_{age} = 22.04 years) and 28 older adults (M_{age} = 69.36 years) in spoken language comprehension under either clear or obscured (i.e., intermixed with background babble noises) audio conditions. The visuals of the speaking mouth and gesturing torsos were manipulated in three ways: with the mouth of the speaker blurred, the mouth clearly visible, and with visible mouth and gestures. Both age groups performed best under clear audio conditions in which the visuals of mouth and gestures were not needed. However, under the obscured audio conditions, younger adults benefited from both the visual mouth and gestures more so than the older adults.

This "less embodied" effect of older adult gesturing appears to be difficult to surmount. An intervention study to train older adults to use gesture-reading to help with their language ability largely failed to produce benefits (Ouwehand et al., 2015). Overall, the evidence on gesture production and comprehension suggests an age-related failure to incorporate the gesturing body into everyday language use, consistent with the proposal of a more muted bodily engagement in late life language.

Multisensory signals in conversation

When conversing, we often use more than the mere audio signals to understand the meaning but rely on the visuals of the speaking mouth as well. This is especially true for seniors, who draw on both auditory and visual inputs to a greater degree than younger adults. Experimenters can explore this question of multisensory integration in language by manipulating the salience of the visual and audio presentation of language stimuli, allowing researchers to gauge the potential multisensory benefits (in cases of intact audio-visual) and detriments (in cases of audio-visual conflict conditions). Unfortunately, the aging and multisensory integration literature has produced mixed results, reflecting the complexities of differing task designs and the specific performance requirements (for review, see Jones & Noppeney, 2021). Yet a common finding is that older adults exhibit increased benefits with audio-visual congruency (Couth et al., 2018; Diederich et al., 2008; Dobreva et al., 2012; Laurienti et al., 2006; Peiffer et al., 2007; Zou et al., 2017), and increased detriments when the audio-visual signals are in conflict (Magnuiness et al., 2011; Mevorach et al., 2016; Poliakoff et al., 2006). Importantly for the EBR effect, the magnitude of multisensory benefits for older adults have been linked to their physicality levels, including physical exercise levels (Mahoney et al., 2015), gait pace (Mahoney & Verghese, 2018), grip strength (Setti et al., 2023), and sit-to-stand speed (O'Dowd et al., 2023). In short, the age-related decrease of physical prowess predicts the increased visual draw on the speaking mouth.

Language comprehension problems for seniors are most apparent in crowded, public spaces where background noises interfere with a clean detection of the auditory signals. In such conditions, older adults will benefit from mouth visuals provided the visual signals are clearly discernible (Gordan & Allen, 2009; Gosselin & Gagné, 2011; Helfer et al., 1998; Huyse et al., 2014; Maguinness et al., 2011; Thompson & Malloy, 2004). For instance, a recent study explored age group differences between younger (M_{age} = 25.29 years) and older (M_{age} = 65.39 years) adults in a simulated cocktail-party setting. They found that while both age groups benefited from audio-visual integration, older adults had a stronger need for both visual intake of the mouth, and for increased cognitive control when processing conflicting audio-visual mismatches (Begau et al., 2022). Visual cues help offset both the processing-speed difficulties that older listeners experience (Pichora-Fuller, 2003), and can 'fill in' the degraded audio signal in cases of hearing loss (Puschmann et al., 2019). Such multisensory benefits are 'superadditive' for older adults, meaning they offer greater benefits than the mere addition of unisensory inputs (Dias et al., 2021).

This increased reliance on visual information is likely a compensatory mechanism to offset auditory and cognitive deficits (Freiherr et al., 2013), and thus its absence can be especially troubling for seniors. Older adults struggle greatly when conversing with speakers whose mouth is occluded (Helfer & Freyman, 2008; Tye-Murray et al., 2016). This multisensory compensation strategy was made clear to many during the Covid-19 pandemic. Mandatory face masks obscure the visual signals of the mouth, much to the detriment of older adults. During the widespread Covid-19 face mask mandates, younger listeners could adapt to the absence of visual signals, whereas older listeners struggled to comprehend language without the visuals (Chládková et al., 2021).

One experimental paradigm that assesses the integration of the audio and visual signals with language sounds is the McGurk effect, in which mismatched visuals of the speaking mouth can alter what is heard. In a typical McGurk effect, participants may hear the syllable "da" when the audio signal is "ba" and the visual mouthing of "ga". Studies have found a heightened McGurk effect in older adults, indicating an increased need for multisensory integration (Laurienti et al., 2006; Peiffer et al., 2007). Importantly, older adults are especially directed by the visual components of the McGurk effect (Cienkowski & Carney, 2002; Gordon & Allen, 2009; Sekiyama et al., 2014). Visual dominance in the McGurk effect is not unique to aging, but rather reflects the increased struggles that older adults have in the face of sensory deterioration and processing speed slowdowns. For instance, a similar visual dominance effect arises in the McGurk effect with younger adults who are bilingual speakers (Marian et al., 2018). Again, chronological years matters less than cognitive and physical status.

General discussion

The evidence presented above supports the contention that EBR effects are subtly but widely present in older adult language ability. Older adults exhibit a shift away from the embodied basis of younger adult language (i.e., language that is smoothly integrated with sensorimotor systems), and towards a more cognitively-driven (i.e., abstract cognitive schemas) language dynamic. It is important to understand that the EBR shift is not merely a result of older adult declines in motor actions but also encompasses declines in interoceptive representations due to senescence of the nervous system, organs, and regulatory processes such as the endocrine and immune systems. Thus, the sources of internal body and motor-action decline are many, will vary based on the task design, and exist at multiple levels.

At the lowest levels, neural signal loss with aging has been well-documented and pervasive across the central and peripheral nervous system (Tran et al., 2020), often linked with age-related decreases in myelination across the nervous system (Verdu et al., 2000) that can result in dedifferentiated cortical responses (Pichot et al., 2022). Interoceptive awareness decreases with advanced age (Khalsa et al., 2009; Murphy et al., 2018; Raimo et al., 2021), due to either increased neural noise within these interior organs, to afferent pathways leading to cortex, or to a combination of both bottom-up and top-down factors (Haustein et al., 2023). As we have documented, overt motor declines and exteroception declines result in a compensatory adjustment evident at multiple levels of older adult language use, ranging from broad performance levels (i.e., gestures, language comprehension), to the semantic processing level (i.e., concrete words, abstract words, action verbs), and at the level of emotionality in language (i.e., semantic representations, alexithymia). In short, age-related physical declines exist across all the visceral and somatic branches of the body. The EBR shift is a compensatory response to these multilevel physical declines through an increase in overt visuocognitive processing.

As applied to language function, the EBR model (as depicted in Fig. 1) is expressed in a wide range of compensatory adjustments: reductions in physiological and motor components to semantics yet increased reliance on feedback-related corrections, offsets to interoceptive deficits through increased reliance on deliberative inner speech, corrections to alexithymia and related interoceptive deficits by focusing on external cues to help them identify their feelings in line with semantic knowledge. Such EBR shifts cannot always offset body-based declines; but when they do, they manage through compensatory increases in the flexibly adaptive visuo-cognitive processing. Note that increased exteroceptive (especially visual) processing is tantamount to increased reliance on the external world as a reference frame (Costello & Aho, 2025), a position argued by Mendes (2010) and MacCormack et al. (2024) regarding emotional processing in older adulthood. Older adults rely on the external world because their internal action models are degraded (Zapparoli et al., 2013, 2016). Much of the decline in the interior models appears to be linked to declines in motor imagery, resulting in increased reliance on the overt visual inspection of the world. Younger adults, in contrast, operate through the smooth automaticity of mental simulations that assist their motor and language engagements.

There is a paradox here: the EBR shift indicates that older adult language is both more abstract and more externally directed. At first blush, this seems almost contradictory. How can older adult language be more abstract and yet, at the same time, be more grounded in the external situational and context cues? The EBR shift is a response to body-based decrements by increasing the weightings towards "situated" and exteroceptive embodiment (especially visual), alongside more abstract representations. We conceptualize this as follows. From an embodied perspective, the various sensorimotor processes help the brain represent the internal state or situation of the body. Yet for older adults, body/action-based declines encourage increased reliance on vision (generally the most information-laden sensory modality) and potentially other exteroceptive or situational sensory feedback. These adjustments help the brain represent the external state or situation of the body—more specifically, how the body as a self is situated with respect to its environment. Visual prioritization is essentially a "best bet" for older adults, as it provides both richer and more resilient information of the world. This is not to say that seniors cannot draw on other sensory modalities for compensation – it is not a question of whether this is possible, but whether it is probable. Not only does vision provides very detailed information about spatial location, target identity, and numerous other essential sources of information, but common sources of age-related decline in vision (e.g., visual acuity loss and presbyopia) can be effectively corrected through eyeglasses. This effect of visual prioritization is pervasive (i.e., is evident across a wide range of language aspects) and subtle (i.e., is not immediately evident outside of experimental protocols), and represents the cumulative adjustments to the neural network that must compensate for decreased physical inputs.

These lifelong adjustments to the mind-body relationship should be understood as a type of neuroplasticity – the gradual reweighting of a complex, distributed neural network that is compensating for the decreased physicality of senescence. The plasticity of neural networks has been well-documented for language processing in older adulthood (see Isel & Kail, 2019). From this perspective, aging is not a story of static and inevitable decline, for the neuroplasticity of older adults operates at both the behavioral and brain levels (Brehmer et al., 2014). Similarly, our approach in this paper is consistent with calls for an integrated bio-cognitive model of aging (Ebaid & Crewther, 2020), which argues that aging requires a multileveled approach that includes the physical alongside the cognitive. Older adult language ability is largely preserved, not despite the physicality declines, but in response to them.

The EBR model and existing neural compensation models

The EBR model proposed in this paper is consistent with several existing cognitive aging compensatory models. Neural compensation models argue that older adults respond to cognitive challenges through a rerouting of their available neural resources, resulting in a preservation of function through patterns of hypo- and hyper-activations within specific brain regions. When older adults perform at equivalent levels with younger adults in cognitive tasks, they frequently do so through bilateral (vs. unilateral as per younger adults) prefrontal activations. This pattern of increased frontal and bilateral activations has been documented in cognitive tasks assessing inhibition control, visual processing, and episodic and working memory, as well as language tasks involving semantic memory (Cabeza et al., 1997) and verbal working memory (Reuter-Lorenz et al., 2000). These hyperactivations are hypothesized to serve as compensatory responses for decreased efficiency in posterior (visual processing) regions relative to more anterior (prefrontal) regions (Davis et al., 2008; Dennis & Cabeza, 2008).[3]

For example, the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH) argues that age-related overactivation of (especially frontal) neural regions represents a compensatory reweighting (Reuter-Lorenz

[3] An alternative interpretation is that prefrontal regions may be more active in late life to compensate for the fact that frontal neurons are less efficient due to structural declines in those regions (Morcom & Henson, 2018).

& Cappell, 2008; Reuter-Lorenz & Lustig, 2005; Reuter-Lorenz & Mikels, 2006). CRUNCH argues that such overactivation is both task dependent (i.e., the more difficult the task, the greater the compensatory reweighting) and age-independent (i.e., operates across the lifespan). Similarly, the Scaffolding Theory of Aging and Cognition (STAC) model argues that the human brain scaffolds its neural resources to restructure brain networks through consistent patterns of over- and underactivations (Park & Reuter-Lorenz, 2009). Importantly for this paper, the STAC model incorporates the concept of brain maintenance, that older adults who have a "more youth-like brain structure" will exhibit more youthful activation patterns (Festini et al., 2018). In short, STAC argues that these compensatory mechanisms are not an aging effect per se but rather exist across the lifespan and indicate the neuroplasticity of the brain.

We find two convergence points between the EBR effect and the CRUNCH and STAC models. First, both CRUNCH and STAC posit that compensatory effects arise across the lifespan (not merely for older adults) and reflect brain flexibility to adjust to performance challenges. The EBR model similarly posits that the reweighting of signals is a direct effect of embodiment rather than aging per se. Accordingly, we hypothesize the testable hypothesis that EBR effects on language should be evident in younger adults who experience physical declines comparable to older adult physical declines. Second, the EBR model argues for age-related visuo-cognitive increases over physical (somatosensory, exteroceptive, and action-perception) processing, a *look-and-think* strategy that redirects attention to the environment. The STAC model similarly recognizes that the compensatory increases in prefrontal areas represent increases in "external guidance" of the environment (Goh & Park, 2009).

The 'how' of the EBR model: predictive coding

A complementary way to interpret the EBR model is through predictive coding accounts of aging (Chan et al., 2021; Moran et al., 2014; MacCormack et al., 2024). Predictive coding or "Bayesian brain" models argue that the brain does not merely react to sensory information but instead builds and uses accumulated "priors" to interpret and react to the world. In early life, when the brain is focused on learning and adapting to its developmental environment, sensory-driven internal models and related neural representations predominate. These sensory-driven processes and behaviors are more reactive, flexible, and thus facilitative to learning, yet they are also more metabolically costly and inefficient. With age, as the brain integrates prior sensory experiences into an accumulated, generalizable set of predictions about the world, it is more efficient to rely on prediction-driven rather than sensory-driven internal models. Not only might prediction-driven internal models become more efficient with age, but they also might become more necessary. Both somatosensory and related motor signals become more noisy, diffuse, and unreliable in late life due to senescence and the higher prevalence of disease or dysfunction. As such, the brain may compensate for these physical difficulties by extrapolating from its accumulated priors.

Predictive coding models are well-suited to explain these EBR effects. If the aging body experiences increasing dysfunction or disease, and the aging brain is increasingly reliant upon its predictions to compensate for these declines, then it stands to reason that older adult language ability and concept formation will similarly become "less embodied." Late-life language should reflect a shift away from episodic and more sensory-driven meanings, and toward more semantically driven and abstract "prediction"-driven meanings.

The 'why' of EBR: older adult reliance on language as social tool

In sum, we have presented evidence *that* these EBR effects exist at multiple levels of older adult language processing, and we have argued *how* these EBR effects exist – namely, through predictive coding changes that mirror the broader "less embodied" changes that attend aging. Yet existing data do not yet explain *why* these EBR changes exist. Are they 'neutral' or benign, merely reflective of the general embodiment changes in aging? Or do they serve a positive purpose? Although it is beyond the purview of this paper to explore this issue at sufficient length, we suggest here that these EBR changes to older adult language may be necessary to allow older adults to rely on language as a social tool.

From the seminal work of Wittgenstein (1953), who equated words to tools in a toolbox, several authors have claimed that words are tools (e.g., Clark, 2012; Tylén et al., 2010). One recent theory of the embodiment of language is that language serves as an inner tool, which transforms and enhances our cognition, and as a social tool (Borghi et al., 2019, 2025; Borghi, 2023). The EBR model suggests that older adults may be relying on the tool of language to a greater degree than younger adults. For all of us, language or words can serve as "essence place-holders" (see Xu, 2002) that link present sensory experiences and inferred meanings to similar prior percepts. Language offers something especially valuable to those (like older adults) who lack the immediacy of the physical – namely, the potential compensation of more abstract, propositional inferences. For example, the word "joy" derives its meaning from prior percepts such as similar previous bodily sensations and actions (e.g., feeling pleasant, accelerating heart, relaxed posture, smiling) or previous exteroceptive sensations (i.e., joyful sights, smells, tastes, sounds, etc.). These links reflect episodic memories and sensory-based knowledge. But the word "joy" can also reflect more abstract, propositional information that has been extracted from prior percepts or that has been acquired through self-insight and shared cultural meanings (e.g., I am likely to feel joyful when I receive good news). These more abstract, summative heuristics reflect propositional knowledge and semantic memory. Older adults can fall back on these more abstract aspects of language.

Language, therefore, helps glue together sensory-predominant episodic data and memories with abstract-predominant semantic data and memories (Borghi & Binkofski, 2014; Borghi, 2023; Lupyan, 2012a, b). It is well-established that aging is accompanied by stronger episodic memory declines relative to semantic memory (Levine et al., 2002; St-Laurent et al., 2011; Vallet et al., 2017). According to predictive coding accounts of aging, if the aging body experiences present-moment dysfunction, the aging brain would increasingly become reliant upon its predictions to compensate for these declines. Accordingly, it stands to reason that for older adult language to be an effective tool, language and concepts will similarly need to become "less embodied" and more reliant on past predictive coding schemes. Predictive coding models are therefore compatible with the EBR effect, as late-life language should reflect a shift away from episodic, more sensory-driven meanings to semantic, more abstract or prediction-driven meanings.

But do older adults rely especially on language as an inner and social tool? We have already discussed the fact that inner speech is preserved and extensively used in older adults, allowing them to enhance their cognition. Furthermore, despite their cognitive and physical challenges, older adults can tell stories and communicate with largely the same fluency that they enjoyed in their youth. Relative to younger adults, older adults produce stories with greater verbosity, syntactic complexity, and propositional density (Gold et al., 1993; Kemper et al., 1990) and connect their autobiographical events into a richer series of life lessons and moral insights (Pasupathi & Mansour, 2006). Older adult stories are more emotionally engaging than younger adult stories (Pasupathi & Carstensen, 2003; Pennebaker & Stone, 2003; Pratt & Robins, 1991), as the latter tend to focus on brevity and facts rather than personal insight and wide perspective (Kemper et al., 2001). Such findings are compatible with research on wisdom writing, wherein older adults have been shown to weave together causal events with moral insights to a far greater extent than younger adults accounts (Bluck & Gluck, 2004).

Older adults may rely on language to provide deeper meaning to their lives. When people narrate their life story, it allows them to weave together the various strands of their life into a more meaningful and emotionally satisfying whole. Storytelling has been shown to be an effective means to improve the happiness and well-being of healthy older adults, evident both in real-time writing tasks (Fang et al., 2023; Mager, 2019) and with digital storytelling formats (Sljivic, Sutherland et al., 2022; Stargatt, Bhar, Bhowmik & Al Mahoud, 2022; Xu et al., 2023). Storytelling is an important example of words as social tools (Enfield, 2024), as it allows one to reexperience an earlier event and therefore offers benefits similar to mental simulation (i.e., when we mentally imagine an event). Mental simulation has been found to have multiple benefits, such as serving as practice for actual physical performances (Kappes & Morewedge, 2016) and helping to provide a more holistic meaning to one's life (Waytz, Hershield & Tamir, 2015). Although older adults struggle to mentally simulate through motor imagery, they can nevertheless leverage the more abstract and social aspects to language to effect comparable effects. Thus, for older adults, storytelling appears to have an adaptive and positive influence on the lives of older adults, offering them the chance to offset their physical and cognitive limitations through reliance on exploration via language. We are suggesting that the internal adjustments of the EBR may be key to older adult reliance on language as a neuroenhancement (Dove, 2020). However, full proof of this possibility is beyond the scope of this paper and would require a separate, future investigation.

EBR effects reflect senescence rather than chronological aging

The EBR effect in older adult language should be interpreted as an age-related *embodiment* effect, rather than as a direct effect of *aging* on language. As older adults age, their physicality declines lead to consequent shifts in how the brain grounds its linguistic categories and concepts. This shift moves the representational continuum away from embodied (e.g., sensory features, action-oriented, concrete) towards more cognitive forms (e.g., mental features, prediction-based, object-oriented, abstract). Importantly, we are not arguing that older adults cannot represent or use more embodied language - again, "less embodied" does not mean "disembodied." Rather, we argue for a gradual and subtle shift in the relative use of embodied forms of language in relation to the individual's degree of biological aging. If older adults are "superagers" or manage to maintain higher levels of physical health, then presumably they will continue to maintain or experience higher levels of embodied language relative to peers with more accelerated physical aging declines.

It is possible to empirically test whether the above age-related linguistics shifts are a direct effect of embodiment. If embodiment changes are the lead causal factor (rather than merely chronological aging), then we would expect similar embodiment-language shifts in younger adults whose embodiment is restricted or enhanced. Consider younger adult athletes with optimal physical functioning. Multiple studies have found that expert athletes exhibit primed processing for action-based and embodied-based language (Debarnot et al., 2014; Gray, 2014), leading to more refined mental representations of action sequences (Abernethy et al., 2005; Aglioti et al., 2008; Güldenpenning et al., 2011; Stadler et al., 2021; Witt et al., 2016). The MNS network is strengthened in expert athletes, offering them simulation of expected motor sequences that sharpen their performance (Yarrow et al., 2009). Similarly, expert table-tennis players demonstrate superior accuracy than novices in both assessing ball trajectory and increased semantic processing within the posterior inferior parietal areas of this network (Wang et al., 2019). Beilock et al. (2008) found that sports experience enhanced action-related word processing, i.e., that novices engaged sensorimotor regions when processing action-related sentences, whereas sports experts recruited greater left dorsolateral premotor cortex, with faster, better language processing. Both physical training and observational learning can prime the action-language relationship (Bidet-Ildei et al., 2020).

Importantly, the converse is also true – people with physical limitations show parallel reductions in embodied language. García and Ibáñez (2018) documented a wide range of movement-based disorders that lead to impairments in action-language processing. For instance, amyotrophic lateral sclerosis (ALS) and motor neuron disease (MND) patients show select deficits in action-based language performance (Sbrollini et al., 2022). Similarly, older adults with Parkinson's Disease exhibit a wide range of motor-based language impairments, such as action verb generation (Bertella et al., 2002; Péran et al., 2009) and action naming tasks (Cotelli et al., 2007; Herrera & Cuetos, 2012; Humphries et al., 2016), with these action-language problems linked to the basal ganglia (Cardona et al., 2013), a group of subcortical brain structures that are directly tied to motor control (Groenewegen, 2003). While inclusion of pathological conditions is outside the domain of this paper, the evidence indicates that the question here is neither of aging nor of disease status - what matters is the state of the body affected by aging or disease.

Thus, we argue that the EBR model reflect senescence (i.e., biological aging of the physical system) rather than aging understood in chronological years. This possibility can be directly tested in several ways. First, by assessing embodied language performance with older adults scored according to physical performance. If our hypothesis is true, we would expect more physically adept seniors (regardless of chronological age) to show higher markers of embodied effects in language. Second, research could compare embodied language components with younger adults in relation to their athleticism. Here, we would expect comparable results – more athletic young adults would evidence more embodied language relative to less athletic young adults. In this regard, age itself is not central to the EBR effect, although older adults are merely the most universally subject to it given their bodily declines.

Limitations and future directions

A limitation to our thesis is that it has been directed largely to healthy older adults, not those who suffer from diseases (e.g., cardiovascular disease, diabetes) or chronic and peak pain conditions. In the case of pain conditions, pain would presumably result in a heightened awareness of the body, and therefore complicate the "less embodied" framework. Yet we do not regard this possibility as necessarily counter evidence to the EBR thesis. Although chronic pain and disease may heighten self-awareness of the body, it could also lead to interoceptive feedback being less salient in two ways: (1) chronic pain conditions may deteriorate the physical structure and function of peripheral/visceral sensations, making those signals less precise and reliable; (2) due to elevated pain and disease, the brain may alter the predictive value of interoceptive signals (as per Bayesian reweighting). In short, chronic pain signals may contain less meaningful information because they are at peak (ceiling) levels and consequently get down-weighted as background noise. From a compensatory perspective, down-weighting chronic pain signals may also serve as a coping mechanism to help the suffering individual. Future work could address how the EBR effect interacts with chronic pain conditions.

Another limitation concerns the scope and granularity of linguistic processing levels addressed in this review. We focused primarily on semantic-level mechanisms due to their strong theoretical grounding in embodied cognition frameworks and their clear links to interoceptive and sensorimotor processes. However, this necessarily leaves out a more fine-grained analysis of linguistic domains such as phonological, morphological, and syntactic processing; modality distinctions (oral vs. written language); and differences across language comprehension and production. Such directions will be critical for a comprehensive account of language processing, and future studies could, for example, test whether EBR-related changes are more pronounced in word-level processing versus sentence-level integration, or whether production and comprehension are differentially affected by reduced embodiment in aging.

Future work could also develop mathematical (especially Bayesian or dynamic system based) models for the EBR effect in older adult language ability. This would be a daunting project, as the myriad body-based causes that would need to be mapped into a quantitative model would be exceedingly large. It would have to encompass the neural, functional and daily-life activities of the NFL model (Kuehn et al., 2018), as well as incorporating both productive and receptive language units. Yet recent work in quantitative language models has started to address this issue quite concretely. Large language models (LLMs) are grappling with how to incorporate embodied dynamics into their algorithms. A recent example is PaLM-E, an embodied multimodal model that has become adept at multiple visual-language performances (Driess et al., 2023). Such models have made strides in the understanding and use of metaphors and figurative language, something that humans can accomplish easily in part because of our embodiment (Wicke, 2023). An EBR effect might be operative with such models. For instance, one LLM adjusted to complex language conditions through increased reliance on closed-loop feedback loops that are tantamount to increased inner monologues (Huang et al., 2022). This is very similar to the hyper-reliance on inner speech we documented earlier, and thus raises the possibility that aging LLM-robotic systems (with declining sensors, motor failures, etc.) could, like aging humans, simulate comparable EBR effects.

Finally, future neuroscientific work mapping the neural and psychological effects of nervous system and visceral signal deterioration would greatly advance a model of EBR effects. Decreased signal salience of somatovisceral and somatosensory sources would not necessarily imply deterioration of the neural pathways themselves. Deterioration could occur at either the quality of the peripheral inputs (e.g., increased neural noise in afferent inputs) or in the communication across and within units (e.g., white matter connectivity issues); or some combination of both. The evidence of the EBR effects we have documented has been largely at the behavioral performance level, and so we are limited in our analyses here. Insofar as language ability is largely preserved in aging, the underlying brain infrastructure appears relatively intact. After all, to achieve the compensation needed for efficient language performance, the language circuitry for older adults must be preserved enough for coherent reweighting of the signals. Consider how the MNS has been implicated in many embodied cognition capacities (Rizzolatti & Craighero, 2004), including the social nature of language processing (Gallese, 2008). Functional activations within this network are largely preserved in non-pathological aging (Farina et al., 2017), suggesting the underlying structures are intact. Yet this network has also been found to undergo age-related cortical thinning (Di Tella et al., 2021). Future work could directly assess the peripheral vs. central dynamic in the EBR effect.

Conclusion

As we age, a broad range of physical outcomes decrease, resulting in decreased salience of both internal motor representations and dampened interoception of internal bodily states. The results are less reliable neural markers for physical inputs and corresponding decreases in predictive power yet also increased weighting for more reliable functions such as information-rich visual processing and the flexibly adaptive cognitive processing. The result of these compensatory adjustments is a shift away from the easy efficiency of embodied immediacy of youth and towards a slower and more deliberative *looking-and-thinking* about the world as external reference. The purpose of this theoretical review paper was to explore whether this age-related "less embodied" effect extends into language capacity, and we found multiple evidence lines justifying this embodiment-based reweighting (EBR) effect. Older adult language is characterized by a downweighing of the physiological-embodied basis of language and an upweighting of the better preserved visuo-cognitive components to language. The resulting shift has a manifold expression: a language ability more driven by higher-order and abstract processing, more dependent on past knowledge and experience gathered across the lifetime, more directed by situational factors and external cues from the environment, greater use of deliberation through inner speech and less dependence on the reflexive use of motor imagery, and greater reliance on prediction-driven rather than sensory-adjusted internal action models. This EBR shift in language is subtle and generally inconspicuous, precisely because it is largely successful in compensating for physiological declines and preserving language capacity. It is also widespread, as it manifests across several language domains, including semantic processing, emotional registration, and conversation capacity. The EBR model offers an essential starting point for future research that can later explore how EBRs are registered at individual processing levels of language domains, such as phonology, morphology, and modality.

Author contributions M.C. wrote the main manuscript text and J.M., E.J.P., U.J., and A.B. contributed to manuscript preparation. All authors reviewed the manuscript.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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