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# Language learning in aphasia: A narrative review and critical analysis of the literature with implications for language therapy

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## ABSTRACT

People with aphasia (PWA) present with language deficits including word retrieval difficulties after brain damage. Language learning is an essential life-long human capacity that may support treatment-induced language recovery after brain insult. This prospect has motivated a growing interest in the study of language learning in PWA during the last few decades. Here, we critically review the current literature on language learning ability in aphasia. The existing studies in this area indicate that (i) language learning can remain functional in some PWA, (ii) inter-individual variability in learning performance is large in PWA, (iii) language processing, short-term memory and lesion site are associated with learning ability, (iv) preliminary evidence suggests a relationship between learning ability and treatment outcomes in this population. Based on the reviewed evidence, we propose a potential account for the interplay between language and memory/learning systems to explain spared/impaired language learning and its relationship to language therapy in PWA. Finally, we indicate potential avenues for future research that may promote more cross-talk between cognitive neuroscience and aphasia rehabilitation.

## 1. Introduction

Language learning is a remarkable human ability that is fundamental for first and second language acquisition and has important practical implications for social interaction and purposeful communication. Learning can proceed at different levels of the complex and multifaceted language system including the phonological structure of the speech signal, the grammatical rules that govern the combinations of lexical and sub-lexical language units, the orthographic representation of such units, and the arbitrary relationships between words and meanings. This last outstanding aspect of language learning, the ability to acquire new words, is the main focus of this review. Humans start incorporating new word forms and meanings into their developing vocabulary from very early on in life, refine their already well-shaped mental lexicons throughout their life span, and continue to show considerable word learning potential despite cognitive decline in aging. A less well understood yet important issue is the integrity of word learning ability in the presence of language impairment due to brain damage and whether memory/learning systems supporting word learning play a role in language recovery.

In aphasia, damage to brain regions responsible for language processing disrupts access to words previously learned and consolidated in the mental lexicon, causing people with aphasia (PWA) to experience word finding difficulties that negatively impact their everyday communication. Anomia is a hallmark deficit that is present in practically all PWA (Laine and Martin, 2006) and is most often attributed to

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*Abbreviations:* PWA, People With Aphasia; STM, Short-Term Memory; WM, Working Memory; DP, Declarative/Procedural; CLS, Complementary Learning Systems; INM, Integrative Neurophysiological Model; MTL, Medial Temporal Lobe; IFG, Inferior Frontal Gyrus; STG, Superior Temporal Gyrus; PMC, Pre Motor Cortex; MTG, Middle Temporal Gyrus; SMG, Supramarginal Gyrus; AG, Angular Gyrus; pSTS, Posterior Superior Temporal Sulcus; RT, Reaction Time; SL, Statistical Learning; CSL, Cross-Situational Learning; AGL, Artificial Grammar Learning.

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impaired access to word representations (Mirman and Britt, 2014). Speech and language therapy is essential for the remediation of anomia (Brady et al., 2016) with treatment plans being largely informed by clinical examinations of language function (Helm-Estabrooks, 2002), and outcome prospects being traditionally related to both lesion site and extent, as well as language ability profile (Watila and Balarabe, 2015). However, not all PWA benefit equally from rehabilitation (Best and Nickels, 2000). Individual variation in treatment response can be observed even across similar anomic profiles (Laganaro et al., 2006) and the mechanisms that underlie treatment efficacy remain unclear (Dignam et al., 2016). This suggests that although understanding the nature of language deficits is necessary (Howard, 1999), it may not be sufficient to develop theory-driven effective therapies (Hinckey, 2002). Furthermore, it underscores the need for considering other factors beyond neural damage and deficits in the language processing system that would predict recovery and guide the development and choice of effective treatments for aphasia.

Notably, the characterization of aphasia has expanded from descriptions of impaired language performance to the identification of other spared and disrupted cognitive processes (Hillis, 2007) associated with language impairment (Wall et al., 2017) and the prediction of treatment-induced language recovery (Dignam et al., 2017). For instance, more current approaches to language processing deficits in aphasia have incorporated verbal short-term memory (STM) (Martin et al., 2018) to emphasize the temporal dynamics involved in the activation of linguistic representations. These can be hampered by weakened activation strength, affecting its transmission, and/ or too-rapid activation decay, affecting its maintenance (Martin and Dell, 2019). Similarly, models of lexical access have considered incremental learning mechanisms that strengthen word-meaning connections after each instance of word retrieval and thus influence subsequent retrieval attempts (Howard et al., 2006; Oppenheim et al., 2010). More generally, learning is inherent to the rehabilitation process (Hopper and Holland, 2005) as it makes possible the acquisition of information and the development of strategies and skills that may enable the recovery or compensation of impaired language function (Nickels, 2002). In fact, the process underlying anomia treatment often has been equated with learning in the aphasia rehabilitation literature, which may reflect the assumption that aphasia therapy is in itself a learning experience, and training specific aspects of language automatically entails the engagement of memory and learning processes (Helm-Estabrooks, 2002). Historically, however, aphasia treatment studies have rarely (i) provided a specific theoretical framework for language recovery that incorporates preserved memory and learning systems, (ii) conducted formal assessments of individual memory and learning abilities as they relate to language treatment response, or (iii) examined whether specific brain regions recruited during language learning are also engaged in response to language therapy in PWA. Therefore, it is possible that assuming a parallelism between language processing and language learning may have undermined the potential use of memory and learning theory and methods in aphasia rehabilitation.

Although the putative overlap in learning and processing has been prevalent in the field of language research, contemporary neurofunctional views consider that language and memory/learning are supported by different neural systems (see Roger et al., 2022 for a review). This motivates the characterization of language learning mechanisms as being used to gain new linguistic information versus the processing of the representations sustaining this information after consolidation. Indeed, language learning proceeds through different phases, from initial encoding to final consolidation, involving different cognitive processes and multiple neural mechanisms that go well beyond those implicated in fully developed language processing (see Section 2). However, while language processing does not fully overlap with memory/learning systems, these systems share anatomical structures (e.g., inferior frontal gyrus, IFG) and cognitive processes (e.g., semantic and phonological STM) that enable their reciprocal communication (see Roger et al., 2022 for a review) and interaction to support the acquisition, maintenance and retrieval of linguistic knowledge (see Rodríguez-Fornells et al., 2009 for a review). A relevant example can be found in learning a new language: while early stages of learning recruit a large brain network of regions involved in language processing, learning, short-term and long-term memory, and cognitive control processes, the end stages after lexical and semantic consolidation (automatization) recruit more circumscribed brain regions associated with the processing of the new lexical-semantic representations (Abutalebi, 2008; Ramos-Escobar et al., 2021). At a more general level, this is consistent with models of cognitive skill learning that describe a shift from highly controlled to more automatized processing during the acquisition of new knowledge or skills (Chein and Schneider, 2012). Similarly, the early stages of language learning also require both the coordinated engagement of specific language and memory systems and domain-general regulatory functions such as attention, cognitive control, and motivation (Laine and Salmelin, 2010; Rodríguez-Fornells et al., 2009; Sliwinska et al., 2017). These domain-general mechanisms can regulate and monitor specialized cortical brain networks involved in word learning (Abutalebi, 2013; Hagoort, 2019; Ramos-Escobar et al., 2021). Thus, the subtle balance between domain-general and domain-specific neural resources can provide a highly flexible system with both short- and long-term brain plasticity to acquire, integrate and automatically retrieve the learned information (Chein and Schneider, 2012; Jeon and Friederici, 2015).

In aphasia, this distinction and interaction between neural systems is highly relevant as lesions resulting in aphasic syndromes mainly affect a left-lateralized brain network of perisylvian regions while rarely affecting directly the medial limbic structures critically related to memory and learning (Ween et al., 1996). Two considerations are worth noting in this context. First, as language processing and memory/learning systems can be differentiated both functionally and neurally, the damage to one system does not necessarily entail damage to the other system. Second, considering the interaction between these two systems in language learning in the healthy adult brain and the possibility that rehabilitation may capitalize on spared cognitive abilities, the recovery of impaired language function may rely on the recruitment of spared memory and learning systems offering a potential route for language recovery (Ween et al., 1996). Therefore, while aphasia therapy has traditionally framed language dysfunction in the context of the "language processing system" alone (Helm-Estabrooks, 2002), re-focusing aphasia research on the interactions between language and memory/learning systems may offer potential to resolve critical open questions and to open a promising path to translate basic cognitive neuroscience into clinical rehabilitation practice.

## 2. Theoretical and clinical relevance of language learning for aphasia

The examination of various aspects of language learning in PWA is of great theoretical and clinical relevance for several reasons. In this review, we particularly highlight word form and meaning acquisition as a relevant facet of language learning that has received the largest attention in the literature, although some points could be similarly raised for other language learning domains as well. From a theoretical standpoint, examining word learning ability in PWA can lead to a better understanding about the interplay between the language processing and language learning systems in the damaged brain, and how this interaction relates to anomia treatment outcomes in aphasia. Learning novel words requires the acquisition of novel word forms, meanings and their associations (Gupta and Tisdale, 2009). Thus, the study of this cognitive ability in PWA may provide important insights into the mechanisms that support anomia therapy which aims to strengthen the links between word-forms and meanings to re-gain access to previously existing yet inaccessible lexical knowledge (Basso et al., 2001; Nickels, 2002). For example, memory and learning systems may help strengthen weakened word form and meaning associations to re-establish lexical access and establish new associations between preexisting or novel linguistic representations. Indeed, it has been proposed that word learning could be a candidate mechanism to facilitate therapy-induced recovery (Basso et al., 2001; Coran et al., 2020) via brain plasticity processes such as the formation of new neural connections (Kelly and Armstrong, 2009). However, examining this possibility involves several considerations. First, theories of memory and learning systems need to be formulated to account for the ways in which cognitive mechanisms that support learning in healthy individuals would operate in the presence of language impairment due to brain damage. Second, appropriate methods need to be identified to demonstrate and explain successful word learning in healthy adult learners which can then be applied to reliable measurements of word learning ability in adults with language deficits. Finally, research designs that combine appropriate assessments of word learning ability and effective language treatment in PWA need to be developed to evaluate and characterize their association.

Understanding word learning dynamics in aphasia can also allow for important inferences regarding the brain regions that are crucial to support word learning in the healthy adult brain and contribute to theoretical accounts of language therapy effects following brain damage. Despite the well-known general effectiveness of language therapy in PWA (Brady et al., 2016), the underlying processes that result in language improvement are yet to be determined (Dignam et al., 2016). If learning processes mediate treatment-induced recovery, then learning theory should be relevant to the construction of a theory of language rehabilitation (Ferguson, 1999). Such a theory should be able to explain the neural bases of the recovery process (Gordon, 1999) and identify the cognitive foundations of behavioral improvement and the procedures that will allow for the desired treatment outcomes (Hinckey, 2002). Cognitive and learning theories together with neurological evidence could offer the best foundations for a theory of aphasia therapy, as they together may help explaining the nature of change beyond the deficit (Hinckey, 2002).

From a clinical standpoint, the study of word learning ability in PWA could inform treatment and prognosis of language recovery. Anomia therapy could benefit from models of word learning ability in neurologically healthy adults (Basso et al., 2001) and methods that promote word learning could be incorporated to individual rehabilitation plans if they show promise to facilitate word retrieval in PWA. If learning is relevant to language therapy, understanding the neural, linguistic and cognitive variables that facilitate or constrain word learning ability will enable greater specificity in treatment planning of aphasia. Specific interventions could then be tailored to target deficits from a more integrative perspective, according to individual profiles of language processing and general cognitive ability, while also taking into account individual learning style and capacity.

A comprehensive assessment of learning ability in PWA might also show independent predictive value on individual potential for recovery and language treatment response. Crucially, no formal systematic methods have been developed to characterize specific learning deficits in PWA, and appropriate tools to assess cognition in PWA are not easily available for clinicians (Helm-Estabrooks, 2002). Aphasia assessment batteries and other diagnostic tools help to identify language domains that require treatment and reveal an individual's residual semantic, lexical and phonological abilities. Although measures of learning ability do not measure potential for recovery or response to treatment per se, they could provide a metric of the functionality of learning capacity that can be used to estimate potential treatment outcomes and the endurance of treatment effects.

All in all, the potential contributions of the study of learning ability in aphasia are manifold, and recent years have witnessed a growing interest in both cognitive neuroscience and aphasia rehabilitation research for the study of language learning ability in PWA. The goal of the present review is to examine this body of research work to characterize patterns of language learning ability and its functionality in PWA, to identify the cognitive and neural mechanisms that support this ability after brain insult, and to evaluate the evidence for a relationship between learning ability and language treatment response in this population. We review these findings in the light of current neurocognitive models of language learning and memory systems that can serve as a theoretical framework to better understand the currently available evidence of language learning ability in aphasia, discuss possible implications of research findings for language rehabilitation, and propose potential avenues of future research.

## 3. Neurocognitive models of word learning in the healthy brain

The core functional components of word learning needed to achieve full mastery of a novel word involve creating a word form representation either alone when novel words are picked from a novel speech signal, or together with a semantic representation (i.e., internal mental representation of any object, action or abstract entity) as well as the receptive and expressive associative connections that allow for their mutual activation (Gupta and Tisdale, 2009). Most theoretical models propose that word learning draws on two aspects of long-term memory, namely the declarative and procedural memory systems, although different aspects of word learning may be supported primarily by one or the other memory system (see Fig. 1 for a depiction of the interaction between language and memory/learning systems in the brain according to the theoretical models considered here).

The declarative/ procedural (DP) model (Ullman, 2001, 2004) assumes that language depends on two critical capacities, namely (i) a stored mental lexicon, comprising a repository of word-specific information including word sounds, meanings and categories (also thought to involve verb arguments, unpredictable forms of words such as irregular past-tense verbs and even idiomatic phrases) and (ii) a computational mental grammar, which entails the rules that govern the sequential and hierarchical combination of language representations that enable speakers to comprehend and produce complex linguistic structures. This model suggests a distinction between memory systems as they relate to different aspects of language processing, such that the mental lexicon relies on declarative memory and the mental grammar is supported by procedural memory. The declarative memory system, involving the hippocampus and other medial temporal lobe (MTL) structures underlying the learning, representation and use of semantic and episodic knowledge, also supports word knowledge in the mental lexicon. This memory system contributes to the rapid learning of new memories and the binding of arbitrary associations which can be consciously and explicitly recollected (Eichenbaum and Cohen, 2001), including the learning of word sounds and meanings and the associative links between them (Ullman, 2001). The DP model assumes that once encoded, memories eventually become less dependent on the declarative memory system and rely instead on neocortical regions supporting different kinds of knowledge, in particular the temporal lobes (Squire et al., 2001) and temporo-parietal areas involved in storing word meaning and phonological representations (Ullman, 2004). In turn, the procedural memory system comprises a specific brain network involving portions of the frontal cortex (Broca's area and supplementary motor area), the basal ganglia, the parietal cortex and the dentate nucleus of the cerebellum (Ullman, 2001). This memory system supports the learning of sensory-motor skills, linear or probabilistic sequences and both linguistic and non-linguistic regularities in general, and enables the gradual and slow implicit acquisition of knowledge underlying the mental grammar (Ullman, 2004). Notably, while this grammatical learning is automatic, does not require conscious control and is not available to conscious access in the native language (Ullman, 2004), the procedural system may become less available to support grammatical learning in a second language in late-language learners (Ullman, 2001). However, increased practice over time may also increase more native-like grammatical knowledge and eventual reliance on the procedural system (Ullman, 2004). Procedural memory also subserves

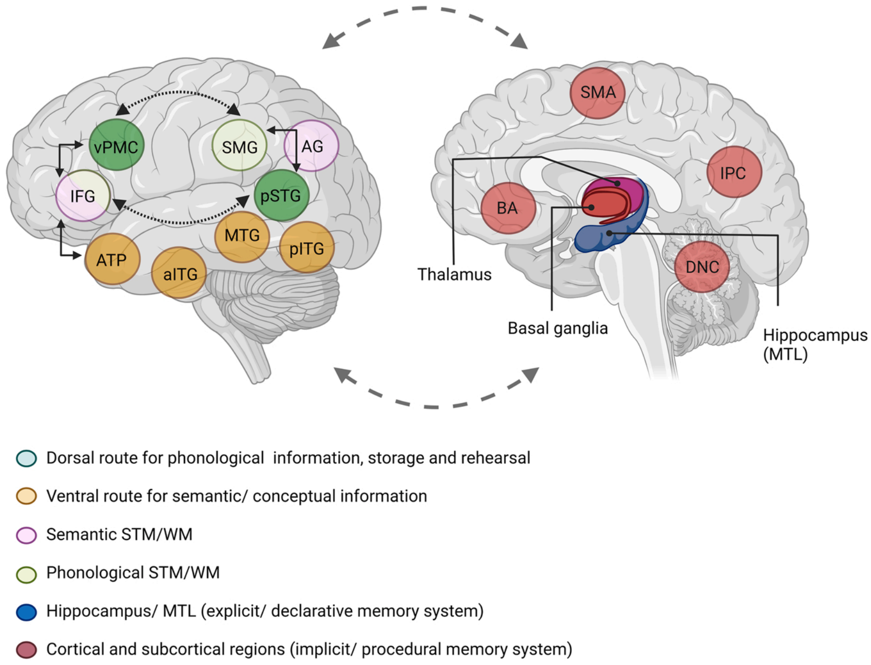

**Fig. 1.** Interaction between language and memory/learning systems in the brain. The left panel shows the brain regions included in the language learning streams of the INM model (Rodríguez-Fornells et al., 2009) with the dorsal audio-motor interface (dark green) sustaining the initial phonological processing and rehearsal of novel word representations during learning (dashed arrows), the ventral meaning interface (yellow), including regions involved in the storage and retrieval of semantic/conceptual information during learning, and critically their interactions (solid line arrows) with brain regions involved in verbal short-term memory (STM)/working memory (WM) supporting the short-term maintenance of phonological (light green) and semantic codes (light purple) during learning (Gupta et al., 2003; Martin et al., 2021). The right panel shows the episodic interface of the INM model including the hippocampus (blue) and other medial temporal lobe (MTL) structures (not depicted here) recruited during the initial encoding and binding of word-referents in explicit associative word learning (CLS model: David & Gaskell, 2009; INM model: Rodríguez-Fornells et al., 2009; DP model: Ullman, 2001, 2004) and its interactions with the dorsal-phonological and ventral-meaning routes (grey dotted arrows) during learning. The brain regions considered to be part of the procedural memory system subserving implicit learning in the DP model (Ullman et al., 2001) are also depicted in this panel (dark red). Although some brain regions supporting memory and learning are expected to be generally well-preserved in post-stroke aphasia (hippocampus/MTL structures), damage to language processing regions may disrupt initial input and output processes for learning and the long-term storage of newly acquired linguistic knowledge, whereas damage to regions supporting verbal STM may hinder the maintenance of novel phonological or lexical-semantic representations during their initial encoding. vPMC = ventral premotor cortex; pSTG = posterior superior temporal gyrus; ATP = anterior temporal pole; MTG = middle temporal gyrus; aITG = anterior inferior temporal gyrus; pITG = posterior inferior temporal gyrus; IFG = inferior frontal gyrus; AG = angular gyrus; SMG = supramarginal gyrus; BA = Broca's area; SMA = supplementary motor area; IPC = inferior parietal cortex; DNC = dentate nucleus of the cerebellum Stated as required by software Biorender. (Created with BioRender.com).

computations across different linguistic domains including syntax, morphology and phonology, in which phonological elements within novel word forms must be combined according to the phonotactics of a language (Ullman, 2013). Neuroanatomically, the basal ganglia and in particular the striatum receive input projections from different cortical regions, especially the frontal cortex (Alexander and Crutcher, 1990; Middleton and Strick, 2000). Within this circuit, the basal ganglia are particularly involved in sequential learning (Janacsek et al., 2020) whereas Broca's area is implicated in working memory (WM) for elements in complex linguistic structures and the learning and processing of sequential and hierarchical patterns over such structures (Ullman, 2004, 2013). The DP model also asserts that while the two memory systems seem largely independent, they interact to enable competitive and cooperative learning such that learning in one system may depress the functionality of the other system (Poldrack and Packard, 2003). Yet damage in one memory system may lead to enhanced learning by the other system, possibly allowing for a compensatory role for language learning in some neurological disorders (Ullman, 2004). Individual variation may exist in the relative dependence on the two memory systems (Ullman, 2004, 2013) and while not all aspects of language rely on memory systems, some may partially rely on memory systems under language breakdown (Ullman, 2013).

Another well-recognized theoretical model of word learning is the Complementary Learning Systems (CLS) account (Davis and Gaskell, 2009; McClelland et al., 1995) which is based on prior models of memory formation (McClelland et al., 1995). This model suggests that lexical acquisition, comprising initial word learning and representation, occurs across two stages. In the first rapid stage of learning, specific encounters with novel words take place and words become initially encoded as sparse context-specific episodic memories supported by the hippocampus and other MTL structures. In the second stage, multiple encounters with novel words over time allow them to become more stable lexical representations (i.e., less context-dependent and more likely to generalize beyond the initial context where they initially occurred) via slow learning and offline consolidation processes taking place in neocortical structures (Davis and Gaskell, 2009). In this way, the neocortex and the hippocampal system conduct complementary learning operations, with consolidation processes mediating between hippocampus-dependent rapid learning and neocortex-dependent slow learning systems, with offline reinstatement of hippocampal memories driving further learning in the neocortex and a gradual reduction in the dependence of memory on the hippocampus (Davis and Gaskell, 2009). This consolidation process also enables newly learned words to become lexical competitors with already existing words of the lexicon, an effect that emerges in the first days after learning and may strengthen over time even up to months (Tamminen and Gaskell, 2008). The neuroanatomical basis of this model is supported by fMRI studies with healthy adults (Breitenstein et al., 2005; Gore et al., 2021; Mestres-Missé et al., 2008) and evidence from developmental amnesia showing impaired learning for names and concepts in the presence of bilateral hippocampal damage (Martins et al., 2006) (although see Hebscher et al., 2019 for evidence of lexical acquisition via rapid cortical encoding that may question the initial necessity of the hippocampus for later instantiation in the neocortex after consolidation). Also, brain regions that fall within the dorsal speech pathway (Hickok and Poeppel, 2007) and show involvement in pseudoword processing contribute to the initial encoding of novel words together with MTL structures (Davis and Gaskell, 2009).

A more extensive theoretical framework is offered by the Integrative Neurophysiological Model (INM) of language learning (Rodríguez-Fornells et al., 2009). It provides an account of the neural substrates and cognitive mechanisms that subserve the acquisition of novel words in natural learning contexts during the initial stages of word learning in early infancy and second language learning. The INM model suggests that infants learn words mostly via implicit learning processes in a seemingly effortless manner and over relatively short periods of time. In contrast, second language learning in adults is more effortful, relies more on explicit learning processes and is modulated by motivational and emotional factors. Near-native language competence can nevertheless be achieved with cognitive control mechanisms aiding the transition from effortful explicit conscious processing to rapid and automatic non-conscious language performance. Despite these differences, the INM model proposes parallelisms between infants and adult learners of a second language in discovering words in connected speech in an unfamiliar language, in mapping of words onto conceptual representations, and in the extraction of meaning from context. Building upon prior evidence, this model suggests that in order to face these challenges, both infant and adult learners can (i) segment speech into word-like units by detecting the distributional probabilities of phonological regularities in the speech signal via statistical learning (Saffran et al., 1996), an ability closely related to other forms of sequential language learning such as artificial grammar learning (Saffran et al., 2006); (ii) resolve the inherent ambiguity of word-meaning relationships in learning contexts (Quine, 1960) via a mapping process in which initially fragile word-referent mappings are updated as possible meanings narrow down to the correct word-meaning associations across multiple learning instances (Rodríguez-Fornells et al., 2009) via cross-situational learning (Yu and Smith, 2007) or hypothesis testing mechanisms (Trueswell et al., 2013); and (iii) acquire novel words from context by allocating attention to the relevant semantic information that allows extraction of the correct word meaning from context via inference and inductive reasoning processes (Mestres-Missé et al., 2007; Rodríguez-Fornells et al., 2009).

The INM model incorporates contributions of the dual stream model of language processing (Hickok and Poeppel, 2000), the role of MTL structures in learning and consolidation (Nadel and Moscovitch, 1997), and the involvement of cognitive control processes in second language learning (Krashen, 1982) to put forth three major brain networks involved in language learning:

(i) *The dorsal audio-motor interface* is consistent with the dorsal language stream (Hickok and Poeppel, 2007) and engages the left posterior temporal regions, the parieto-temporal boundary, and the frontal regions subserving motor speech representations. It is involved in the mapping of sounds onto articulatory-based representations (Hickok and Poeppel, 2000) and the extraction of phonological structure (Hickok and Poeppel, 2007) important for the initial learning of novel phonological word forms. Regions of this left frontotemporal brain network including the superior temporal gyrus (STG), the prefrontal motor cortex (PMC) (Cunillera et al., 2009; McNealy et al., 2006) and the pars opercularis and pars triangularis regions of the left IFG (Karuza et al., 2013) as well as the dorsal white matter pathways connecting these regions (López-Barroso et al., 2013), have been involved in adult speech segmentation via statistical learning. This suggests that this pathway may enable learners to generate a sensory representation of the sound sequences embedded in novel words that can be mapped onto motor articulatory sequences, helping recently segmented words remain active in phonological STM (Rodríguez-Fornells et al., 2009) via rehearsal mechanisms (López-Barroso et al., 2011).

(ii) *The ventral meaning interface* corresponds to the ventral language stream (Hickok and Poeppel, 2007) which is crucial for mapping sound onto meaning and includes regions such as the medial, inferior and anterior temporal cortex, the ventral IFG, and orbital, medial and ventrolateral prefrontal cortex, and white matter pathways mediating the connections between these and other regions including the inferior longitudinal, inferior fronto-occipital and uncinate fasciculi (Rodríguez-Fornells et al., 2009). This interface is engaged when meaning for a novel word needs to be inferred from a context or from discourse and when conflicting conceptual information requires disambiguation to correctly identify meaning in a learning context. Temporal regions are important for accessing lexical-semantic and conceptual representations (Saur et al., 2008) while prefrontal regions have been implicated in the selection of semantic features and controlled semantic retrieval (Thompson-Schill et al., 1997). Both the left anterior IFG and the left MTG have been implicated in learning novel word meanings from context (Mestres-Missé et al., 2008) and the ventral white matter pathways have been found to contribute to learning novel word-referent mappings and extracting word meaning from context (Ripollés et al., 2017).

(iii) *The episodic-lexical interface* is associated with the declarative memory system involved in the creation of episodic memories and the acquisition of lexical and semantic information (Rodríguez-Fornells et al., 2009). Similar to other models (Davis and Gaskell, 2009; Ullman, 2001, 2004), the initial binding of a novel word form to a conceptual representation is considered to be initially MTL-dependent and become more context-independent via long-term consolidation into the mental lexicon (Rodríguez-Fornells et al., 2009). Different studies have provided evidence of the particular involvement of the hippocampus in novel word learning (Breitenstein et al., 2005; Gore et al., 2021; Mestres-Missé et al., 2008), and potentially the white matter pathways interconnecting these MTL structures. These pathways include the inferior longitudinal fasciculus (Rodríguez-Fornells et al., 2009) extending from the ventral and lateral temporal cortex to the posterior parahippocampal gyrus (Schmahmann et al., 2007).

The three language learning interfaces interact cooperatively in novel word learning, and this interaction is modulated by cognitive control mechanisms and inductive reasoning mediated by the middle prefrontal cortex. Also, the striato-thalamic circuits might play an integrative role between the different inputs from the three interfaces, the cortical regions involved in executive functioning, attentional processes and WM. Finally, the model also assumes that language learning is modulated by reward-motivation subcortical systems as well as feedback processing (see Ripollés et al., 2014, 2016).

While these three theoretical models make unique contributions to our understanding of word learning, they mostly agree on the memory systems and brain regions involved in the process of learning words and meanings, and seem compatible with the view that STM/WM mechanisms also support language learning. STM refers to the capacity to maintain a limited amount of information in an active state keeping it temporarily accessible for a limited amount of time (Cowan, 2008). STM can be conceptualized as being part of WM, a related construct that was put forth as a multicomponent memory system to account for different types of temporary memory and to include both storage and processing operations (Cowan, 1996, 2008). Studies framed as examining STM and WM have made important contributions to our current understanding of language learning, although as stated by Cowan (2008), the term WM became largely dominant in the field after the influential model proposed by Baddeley and Hitch (1974) demonstrating that temporary memory could not be explained via a unitary construct. In this model, WM involved the phonological loop and the visuospatial sketchpad as two separate storage systems for verbal and visual-spatial representations governed by a central executive control system (see Baddeley, 2003 for a review). The phonological loop allowed the system to temporarily hold language memory traces via the phonological store and to keep them accessible via articulatory subvocal rehearsal. As such, the phonological loop was proposed as a “language learning device” that evolved to facilitate language acquisition (Baddeley et al., 1998) as demonstrated in children (Gathercole and Baddeley, 1990), healthy adults (Gupta, 2003) and neurologically impaired populations (Baddeley et al., 1998). A more recent model proposed by Gupta (2003) offers a complementary account of the interactions between word learning, nonword repetition and immediate serial recall by assuming that verbal STM mechanisms operate on language representations at the lexical level. In this model, a short-term sequence memory component encodes and temporarily maintains the serial order of activation of representations (i.e., words in immediate serial recall of word lists, novel word forms in new word learning or nonwords in nonword repetition) at the lexical and sub-lexical level following speech input, allowing the accurate sequence recall in serial order. This facilitation of maintenance would allow for the eventual learning in the long-term connections between the lexical and sublexical level (Gupta, 2003). Although these models (Baddeley, 2003; Gupta, 2003) focus predominantly on the phonological aspects of language maintenance and rehearsal in STM/WM, there is evidence of separable systems of phonological and semantic STM/WM maintaining these types of linguistic information (Martin et al., 1994; Martin and Saffran, 1997; Shivde and Anderson, 2011; see Martin, 2005 for a review). Recent research conducted by Martin et al. (2021) using the lesion-symptom mapping approach suggests different neural bases for phonological and semantic WM. For phonological WM, their study uncovered the supramarginal gyrus (SMG) which would support phonological storage, and other cortical and subcortical regions including supplementary motor and posterior IFG regions that would contribute to articulatory and motor planning processes involved in subvocal rehearsal. In turn, for semantic WM, the study uncovered the opercular left inferior frontal region as possibly linked to semantic selection and maintenance, the angular gyrus (AG) which would contribute to meaning integration and the posterior superior temporal sulcus (pSTS) which may be involved in linking lexical-phonological and semantic representations and maintaining word meanings in phrase processing (Martin et al., 2021). Altogether, these models provide a theoretical and neuroanatomical framework to understand interactions between language processing and memory/learning systems in aphasia.

## 4. Studies of language learning in aphasia

### 4.1. Search strategy and organization

In this review, our search strategy included the PubMed and PyschINFO databases using the following keywords and boolean operators: “aphasia” AND “learning” OR “word learning” OR “language learning”. Publications were screened by title and abstract. Given that this review focused on language learning in aphasia, the following inclusion criteria were used: (a) participants diagnosed with post-stroke aphasia, (b) report of measurements of language learning performance in which learning is measured via experimental tasks independently from treatment, (c) learning paradigms involving the acquisition of either partial or fully novel linguistic information encompassing unfamiliar or novel words, conceptual referents, definitions, or item sequences, allowing to differentiate between retrieval from long-term memory information alone and actual acquisition of partial or fully novel information, (d) published peer reviewed journal article, (e) publications in English only. There were no date restrictions and the search was conducted until August 1, 2021. In consideration of the goal of this review, we excluded studies that equate treatment to learning (studies that involve treatment alone and use the terms learning and treatment interchangeably), or incorporate memory and learning principles in treatment without measuring verbal learning (the acquisition of either partially or fully novel linguistic information) separately. These studies were excluded since their focus on re-establishing language function (e.g.: access to previous familiar words) would not allow us to assess the integrity of learning ability in aphasia per se, which is necessary to inform how specific forms of language learning are associated with language treatment effects in aphasia. Finally, we also excluded studies including stroke patients with no independent analyses reported for just PWA. Twenty-eight studies met the eligibility criteria and were considered for appraisal. This section is organized to review the main findings from these studies examining different aspects of language learning in aphasia employing both group, case series and single-case designs largely distributed across different methodological approaches and learning paradigms. Studies are organized into explicit, implicit and incidental learning with subsections discussing the main findings within each line of research, and the relationship between learning ability and response to language therapy in PWA. Tables 1–4 summarize the methodological approach and main findings of the studies reviewed in each section whereas Figs. 2–4 exemplify the learning materials, learning task designs and findings reported by a few studies included in this review.

### 4.2. Explicit language learning in aphasia

Explicit learning entails the acquisition of declarative memories as flexible representations which are accessible to conscious recollection (Ullman, 2001) and enables the associative binding of items or events (Eichenbaum and Cohen, 2001) via slow learning and consolidation (Davis and Gaskell, 2009). In line with this view, studies of explicit word learning in aphasia have used methods that (i) overtly instruct participants to learn a given training set, (ii) test their ability to explicitly demonstrate the acquired knowledge and (iii) measure long-term consolidation via follow-up assessments. Most studies have employed associative learning paradigms drawing on binding processes that link single words to conceptual referents (i.e., systematic mappings) and often include a learning phase that requires learning single word-picture pairings presented in the visual, auditory or combined modalities, and a test phase that enables evaluating word learning success via recall and recognition measures. Other studies employing paired-associate paradigms are also reviewed in this section (see Table 1 for a summary of these studies).

It is also worth noting that studies in this section have employed a variety of stimuli including unfamiliar words, novel word-known referent pairings (e.g., Freed and Marshall, 1995, Marshall et al., 1992, 2001), or known word-novel referent pairings (Freed et al., 1995) as opposed to truly novel word-novel referent associations (see Gupta et al., 2004 for space aliens, and Laine and Salmelin, 2010 for the Ancient Farming Equipment, AFE paradigm) (Fig. 2). While the first type of stimuli offers a naturalistic approach to word learning, the second approach can be considered a ‘pure’ measure of learning ability (Tuomiranta et al., 2014a) since learners need to encode truly unknown phonological and conceptual representations as when learning words in the native language (Gupta, 2003). Different from the first method, the use of unknown stimuli with no available representations in the language system may (i) minimize compensatory influences of prior vocabulary experience (Marshall et al., 1992) and the reliance on existing representations to support learning, (ii) enable valid individual comparisons among PWA and group comparisons across aphasic and healthy speakers since trained materials are equally unknown to all participants, and (iii) eliminate potential confounds of psycholinguistic properties that may influence the retrieval of known words which further complicates the assessment of the integrity of learning in aphasia (Tuomiranta et al., 2012). Although different, both approaches provide valuable complementary information about word learning in aphasia.

#### 4.2.1. Receptive and expressive word learning

Most studies have referred to the ability to learn words by means of how the acquisition of lexical knowledge is trained or measured in PWA. Receptive learning refers to word learning ability as demonstrated via recognition, which requires deciding whether a trained item is old or new, or identifying trained items among foils. In this way, learning is demonstrated via receptive processing abilities alone. In turn, expressive learning consists of the demonstration of lexical acquisition via

**Table 1**
Studies of explicit language learning in aphasia.

| Study | ***Participants*** | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| Marshall et al. (1992) | 23 PWA<br>8 HC | 12 real word-novel symbol pairings (1 set per condition). | *Design:* four facilitation tasks (word-referent matching tasks in the visual, auditory, visual + auditory modality and a non-rehearsal condition), and four cueing tasks (repetition, self-cueing, determinate and indeterminate sentence completion).<br>*Duration:* 2 sessions. | – Accuracy during training.<br>– Naming probes after each training block, and 1 week after training. | – Accuracy below HC but improved in all training conditions (highest on the repetition condition).<br>– Naming probes were significantly greater in cueing relative to facilitation conditions (highest on the selfcueing condition).<br>– Decrease naming at 1 week in all conditions, greatest maintenance in self-cueing. | – NS |
| Freed and Marshall (1995) | 10 PWA and 10 HC | 20 trained unknown word- picture pairs (dog breeds) and 20 control pairs (dogs and birds). | *Design:* associative learning via self-cueing (based on semantic and visual features).<br>*Duration:* 12 sessions (4 weeks). | – Naming probes without cueing 1 week and 1 month after training. | – Learning performance below HC in all 3 sets.<br>– Better naming for trained versus untrained items.<br>– Durable learning effects at 1 week and 1 month testing. | – NS |
| Freed et al. (1995) | 30 PWA (15 in each condition) | 30 real word-abstract symbol pairings (20 training and 10 control pairings). | *Design:* associative learning via self-cueing (self-generated associations based on semantic and visual features) versus provided cueing (ready-made associations based on semantic and visual features made by the first group of PWA but provided by the examiner).<br>*Duration:* 6 sessions. | – Naming accuracy during training after cueing.<br>– Accuracy on a mid-training naming probe, a post-training probe and on 3 follow-up naming probes (1 day, 3 and 30 days after training) without cueing.<br>– Accuracy on 1 cued naming probe 1 month after training. | – Naming accuracy was superior in the self-cueing group relative to the provided cueing group early in training.<br>– Both cueing procedures led to comparable accuracy on mid-training, post-training and follow-up naming probes showing similar maintenance 30 days post testing.<br>– Both groups showed similar improvements on control items during training.<br>– Naming accuracy did not show significant improvements on the cued naming probe relative to the final non-cued naming probe 30 days post training for any of the two groups. | – Aphasia severity was not associated with accuracy on the 3 naming probes at follow-up testing. |
| Freedman and Martin (2001) | 5 PWA (EA, ML, AK, GR, AB) and 8 HC | -32 English known word-Spanish unknown translation pairs (phon. learning task).<br>-32 known English word-unfamiliar definition pairs (lex-sem. learning task). | *Design:* pair-associate paradigm with auditory presentation of associate pairs followed by a test phase (presenting the initial spoken item of a pair for recall of the associated word).<br>*Duration:* 1 session. | – Accuracy in tests of phon. and lex-sem. learning. | – Learning accuracy and rate below HC who showed better semantic than phon. learning. | – Relatively spared phon. and semantic processing.<br>– Learning profiles in line with verbal STM deficits: EA = severe phon. STM deficit + better preserved semantic STM + better semantic than phon. learning. ML, AK, GR = greater deficits in semantic STM + better preserved phon. STM + better phon. than semantic learning. AB = severe deficits in both types of verbal STM + impaired learning in both tasks. |
| Marshall et al. (2001) | 30 PWA (15 per condition) | 20 unknown word-unfamiliar picture pairings (dog breeds). | *Design:* associative learning via self-cueing (semantic and visual features) versus phonological cueing (first phoneme and number of syllables).<br>*Duration:* 12 sessions. | – Accuracy during training.<br>– Naming probes without cueing 1 week, and 1 and 6 months after training. | – Learning observed in both conditions after training.<br>– Superior naming accuracy and maintenance at 6 months in the self-cueing condition. | – Aphasia severity associated with learning (phonological cueing). |

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**Table 1** (*continued*)

| Study | *Participants* | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| Marshall et al. (2002) | 15 PWA and 15 HC | 20 unknown word-unfamiliar picture pairings (dog breeds). | *Design:* associative learning via self-cueing (feature cues, visual trait cues, experiential cues, rhyme cues or combined semantic + phon. cues based on information provided prior to training).<br>*Duration:* 4 weeks (3 sessions per week). | – Naming probes 1 week, and 1 and 6 months after training | – No specific type of cue provided significantly superior naming benefits for the HC.<br>– For PWA, semantic cues (feature cues, visual trait cues, experiential cues) provided significantly superior naming benefits relative to rhyme cues and combined cues. | – NS. |
| Kelly and Armstrong (2009) | 12 PWA | 20 novel word-picture pairings (creatures) and their semantic features: skills, habitat and food (5 items per training session). | *Design:* associative learning via varying methods (e.g.: passive listening and copying written new words).<br>*Duration:* 4 training sessions and 1 follow-up testing session. | – Averaged scores on verbal and written recall, lexical decision, syllable matching, word-picture matching, picture-syllable matching, categorization and reading. | – Wide variation in learning ability and maintenance at follow-up.<br>– Superior learning performance in recognition memory relative to verbal recall. | – NS. |
| Tuomiranta et al. (2011) | 2 PWA (QH and IU) and 2 HC | 20 novel pseudoword-novel picture pairings (tools[a]): 10 pairs trained with only labels and 10 pairs trained with labels and definitions. | *Design:* explicit associative learning via repetition. Learning of semantic definitions via passive exposure.<br>*Duration:* 4 training sessions and 5 follow-up sessions. | – Recognition for trained versus untrained items.<br>– Naming tests with and without phon. cueing.<br>– Recognition for the presence and content of semantic information (incidental learning). | – Explicit learning and maintanance below HC.<br>– Near-ceiling recognition at follow-up for both PWA.<br>– Superior naming for QH relative to IU after training.<br>– Maintenance of cued naming (QH= 4 weeks; IU= 1 week).<br>– Both PWA showed incidental learning, with larger recall decay for IU relative to QH. | – QH with superior learning performance also showed spared lex-sem. processing ability and better nonword repetition relative to IU.<br>– IU with lex-sem. impairment also showed worse incidental semantic learning. |
| Tuomiranta et al. (2012) | 2 PWA (LL and AR) and 2 HC | 20 unfamiliar realistic word-novel picture pairings (tools[a]): 10 pairs with only labels and 10 pairs trained with labels and definitions. | *Design:* explicit associative learning via repetition. Learning of semantic definitions via passive exposure.<br>*Duration:* 4 training sessions and 5 follow-up sessions. | – Recognition for trained versus untrained items.<br>– Naming tests with and without phon. cueing.<br>– Recognition for the presence and content of semantic information (incidental learning). | – Explicit learning and maintanance below HC.<br>– Near-ceiling recognition at follow-up for both PWA, with some decline for AR.<br>– Superior naming for LL relative to AR after training.<br>– Maintenance on cued naming (LL= 6 months; AR= 8 weeks).<br>– Better incidental learning for LL, faster recall decay for AR. | – LL with better word learning also showed more spared lex-sem. processing, pseudoword repetition and verbal STM relative to AR. |
| Kroenke et al. (2013) | 12 PWA | 30 pairings of pseudowords and videos of meaningful iconic gestures (1 set of 15 items per modality varying across three levels of phonological complexity). | *Design:* associative learning in a gesture-mediated versus verbal modality.<br>*Duration:* 4 sessions. | – Cued recall after training (expressive learning) with cues being the real words of manipulable objects. | – Significant learning over time regardless of condition.<br>– Better learning for phon. simple relative to complex pseudowords. | – Better lexical-semantic processing and worse phonological processing were associated with larger benefit from gesture-mediated learning.<br>– Lexical-semantic ability and phonological working memory predicted the gesture benefit effect.<br>– Higher frequency of damage to the left inferior frontal gyrus and the anterior and medio-temporal giri observed in patients with worse gesture-mediated learning. |
| Tuomiranta et al. (2014a) | 1 PWA (TS) and 6 HC (Exp. 1 only) | *Exp. 1:* 20 novel word-picture pairings (tools[a]).<br>*Exp. 2:* 4 sets of 15 novel word-picture pairings each. | *Design: Exp. 1*: associative learning (auditory + orthographic modality).<br>*Duration:* 4 training sessions and 5 follow-up sessions up to 6 months post-training. | – *Exp. 1:* naming tests during training and oral and written naming at follow up (tested separately).<br>– *Exp. 2:* naming tests in the same modality as | – *Exp. 1:* above chance naming 1 day post-training for both modalities, comparable to HC in the written modality.<br>– Better maintenance for written than oral | – Repetition (phonology) better than reading (orthography) ability suggesting language profile opposite to learning profile. |

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**Table 1** (*continued*)

| Study | *Participants* | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| | | | *Design Exp. 2*: associative learning in 4 conditions combining auditory/ orthographic (input) and spoken/ written naming (output).<br>*Duration:* 2 training sessions per condition. | the output modality during training. | naming, up to 6 months with cues.<br>– *Exp. 2:* learning in all conditions with superior naming and long-term retention in the orthographic input-output condition.<br>– Summed naming in orthographic input conditions superior to naming in auditory input conditions.<br>– Similar results in the output conditions. | |
| Wang et al. (2020) | 11 PWA, 18 older HC and 18 young HC | 1 set of 30 low frequency noun pairs with weak semantic associations (linguistic learning task) and 1 set of 30 pairs of real-life complex scenes (non-linguistic learning task) per learning condition. | *Design:* explicit paired-associative verbal and non-verbal learning across two conditions: massed retrieval practice (no intervening trials) and spaced retrieval practice (four intervening trials) with feedback.<br>*Duration:* 1 training and testing session and 1 additional testing session. | – Accuracy on massed and spaced retrieval practice trials during learning.<br>– Immediate cued recall.<br>– Delayed recognition (session 2).<br>– Delayed cued recall (session 2). | – Learning patterns similar to HC, reduced accuracy during learning and on recall relative to controls, comparable delayed recognition.<br>– Better learning for word pairs relative to picture pairs, similar to controls.<br>– Superior retention for massed relative to spaced retrieval practice during learning.<br>– Superior retention for spaced relative to massed retrieval practice on both immediate and cued recall and delayed recognition (within-HC range), regardless of stimuli type. | – NS. |
| Bormann et al. (2020) | 1 PWA (IS) and 11 HC in Exp. 1, 8 HC in Exp. 2 and Exp. 3. | *Exp. 1*: 8 familiar picture-word pairs and 8 familiar picture-nonword pairs.<br>*Exp. 2*: 8 color-nonsense compound noun pairs (control: 8 color-single noun pairs).<br>*Exp. 3*: 24 unknown tool-nonsense compound nouns and function information. | *Design Exp.1:* associative learning with exposure followed by immediate expressive recall.<br>*Duration:* 1 session.<br>*Design Exp. 2*: associative learning with exposure followed by immediate expressive recall and delayed recall.<br>*Duration:* 2 sessions (1 month apart), 1 condition per session.<br>*Design Exp. 3*: associative learning with exposure followed by immediate expressive recall and delayed recall. | – *Exp. 1*: Accuracy on expressive recall.<br>– *Exp. 2 and 3:* Accuracy on immediate and delayed expressive recall. | – *Exp. 1*: IS learned all words comparably to HC, but showed impared nonword learning.<br>– *Exp. 2*: IS learned all single noun-color pairs comparably well to HC, but also showed significantly poorer learning of compound nouns and color pairs on immediate and delayed recall.<br>– *Exp 3*: IS showed impaired learning of compound nouns relative to HC but could learn the semantic information of the trained items comparably well to HC. | – IS presented poor verbal STM comprising impaired word and digit spans and sentence repetition. |
| Coran et al. (2020) | 3 PWA (KT, UP, CN) | 2 sets of novel word-referent pairings (aliens[b]) for rcceptive (n = 10) and expressive (n = 10) training. | *Design:* explicit novel word-learning comprising receptive and productive learning. *Duration:* one session. | – Accuracy on expressive recall (naming test).<br>– Accuracy on recognition test (pointing to a trained item among 4 alternatives). | – UP showed full receptive acquisition (10/10) with minimal expressive learning (1/10, proportion of correct phonemes = 0.24).<br>– CN demonstrated significant receptive learning (8/10) but expressive learning was at floor levels (0/10).<br>– KT showed impaired receptive (2/10) and expressive (0/10) learning. | – UP with better integrity of the left arcuate and inferior longitudinal fasciculi.<br>– CN showed relative good presentation of ventral white matter tracts.<br>– KT had larger lesions and disconnection of dorsal and white matter tracts. |

PWA = people with aphasia; HC = healthy controls; NR = not reported; NS = not studied; Exp = experiment; STM = short-term memory; F = frequency; I = imageability; Phon = phonological; Lex-sem = lexical-semantic.

[a] Tools from the “Ancient Farming Equipment” (AFE) paradigm (Laine and Salmelin, 2010).

[b] Aliens from the “Space aliens and nonwords” paradigm (Gupta et al., 2004).

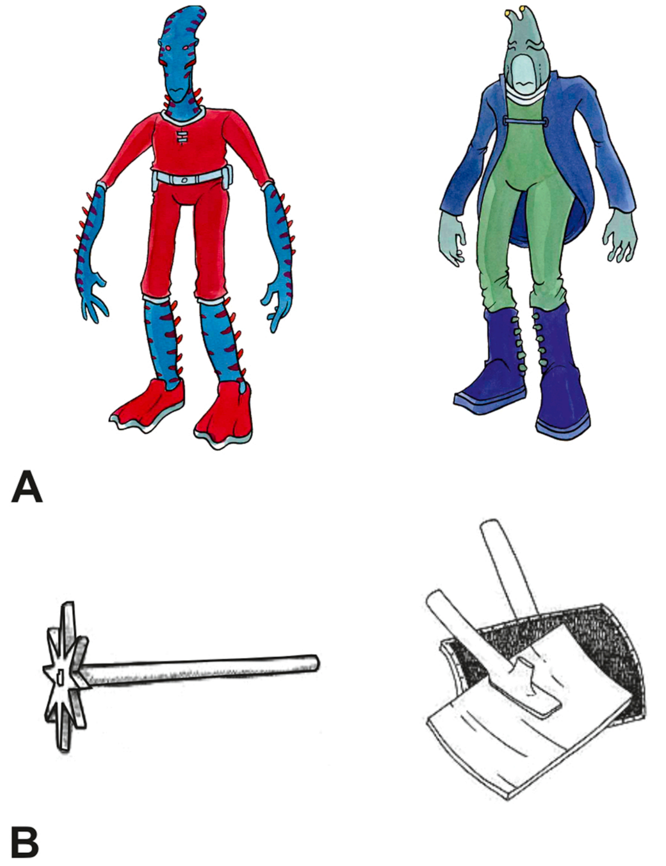

**Fig. 2.** Stimuli used in studies assessing novel word learning in aphasia. Example of visual referents used in learning paradigms comprising the acquisition of novel word-referent pairings. Panel A shows exemplars of aliens from the Space Aliens and Nonwords paradigm (Gupta et al., 2003) whereas panel B presents tools from the Ancient Farming Equipment (AFE) paradigm (Laine and Salmelin, 2010).

measures of expressive recall such as producing the trained items in response to verbal or pictured cues. As such, learning is evidenced via expressive processing abilities entailing the oral or written production of the trained items. Overall, studies of word learning have shown that PWA can demonstrate explicit associative learning of single word-referent mappings involving either familiar or novel stimuli, albeit below healthy control levels (Freed and Marshall, 1995; Marshall et al., 1992; Tuomiranta et al., 2011, 2012). PWA show a large individual variation in word learning performance, with this ability being more robust for receptive than expressive learning (Coran et al., 2020; Dignam et al., 2016; Kelly and Armstrong, 2009). Studies suggest that receptive measures can provide a reliable metric of learning ability for novel linguistic information after training (Coran et al., 2020; Dignam et al., 2016; Kelly and Armstrong, 2009; Wang et al., 2020), bypassing the high demands that verbal recall measures pose on speakers with word retrieval limitations. Moreover, as receptive learning scores are associated with anomia treatment success in PWA (Dignam et al., 2016), receptive measures alone could provide a practical metric sufficiently sensitive for prognostic purposes.

On the other hand, evidence on expressive word learning indicates that verbal retrieval of trained words can be challenging for PWA (Coran et al., 2020; Dignam et al., 2016; Kelly and Armstrong, 2009; Tuomiranta et al., 2011, 2012), especially when words are phonologically complex (Kroenke et al., 2013) or entail compound nouns (Bormann et al., 2020). Only one study found superior performance on productive relative to receptive measures of word learning (Marshall et al., 1992), but this pattern of results may have been facilitated by the type of learning materials (i.e., unfamiliar real words as opposed to nonwords), an intensive training schedule and a sample including mainly mild aphasic participants. These findings suggest that while expressive recall can provide a realistic measure of learning and individual improvement on single word production, learning ability measured via expressive recall could be also confounded with lexical access deficits common in aphasia (Laine and Martin, 2006). Thus, expressive word learning deficits in at least some PWA may be functionally associated with language output deficits (Ween et al., 1996), reflecting constraints of the language production system on verbal demonstrations of learning capacity.

### 4.2.2. *Facilitation of explicit word learning*

Research suggests that certain manipulations during associative word learning may help receptive learning in PWA. For instance, massed retrieval practice can promote more effective immediate learning of noun and scene picture pairs relative to spaced retrieval practice in PWA, while the latter can lead to better retention regardless of stimulus type (Wang et al., 2020). According to the authors, massed practice may improve immediate retrieval drawing on direct retrieval from STM, while spaced retrieval practice may improve later recall by allowing memory traces to fluctuate between encoding and retrieval, leading to better retention. Gestures can also aid novel word learning when trained words represent manipulable objects as demonstrated in individuals with mild aphasia showing better lexical-semantic and worse phonological processing abilities (Kroenke et al., 2013). Also, four other studies have shown that expressive learning in PWA can be facilitated by self-generated cues based on individually chosen semantic information to aid the effective recall of trained words (Freed and Marshall, 1995; Marshall et al., 1992, 2001). Findings suggest that self-generated cueing which requires more effortful and in depth-processing (Craik and Lockhart, 1972) can lead to superior expressive learning relative to learning via repetition and sentence completion (Marshall et al., 1992), phonological cueing (Marshall et al., 2001, 2002) and combined phonological-semantic cueing (Marshall et al., 2002). This is the case especially when self-generated semantic cues capture specific object features, visual properties or experiential information based on general world knowledge (Marshall et al., 2002). Nonetheless, while self-generated cues provide a benefit during early training as compared to cues provided by the examiner, both types of cueing procedures lead to comparable learning outcomes and long-term maintenance (Freed et al., 1995). Overall, these findings highlight the relevance of semantic information as a cue for learning beyond the contribution of who generates or provides the cue for retrieval. Finally, although it has been proposed that expressive learning could be facilitated by preceding receptive training of the same items (Martin et al., 2012), PWA may show variable degrees of expressive and receptive learning when both approaches are combined (Coran et al., 2020). More research is needed to determine whether the use of specific training regimes and the integration of both receptive and expressive processing may benefit both word learning and treatments for naming deficits in aphasia.

### 4.2.3. *Orthographic versus auditory explicit word learning*

Studies have shown that written naming can be superior to oral naming when measuring word learning ability in PWA (Kelly and Armstrong, 2009) and it can aid both learning of novel word-referent pairings and anomia treatment in aphasia (Laganaro et al., 2006). These studies suggest that written production may offer an alternative output channel for expressive word learning ability and anomia therapy although they have not directly compared written versus oral naming in learning. Two single-case studies have examined the effects of sensory modality (i.e., orthographic versus auditory) on explicit word learning in aphasia (Tuomiranta et al., 2014a, 2014b). Their results showed that (i) some PWA demonstrate superior novel word learning in the visual-orthographic modality relative to the auditory modality (Tuomiranta et al., 2014a, 2014b), (ii) learning performance in the written modality can be comparable for PWA and healthy controls (Tuomiranta et al., 2014a, 2014b), (iii) orthographic visual input and written output can lead to superior learning relative to auditory spoken input and spoken output (Tuomiranta et al., 2014a); (iv) spared orthographic word learning can be used to successfully re-learn vocabulary (Tuomiranta et al., 2014b), and (v) spared orthographic word learning may by supported by extensive recruitment of intact right hemisphere regions despite left hemisphere damage affecting phonological processing and learning via the auditory modality (Tuomiranta et al., 2014b) (Fig. 3). It is worth noting that although spared word learning via orthography has been reported in patients with phonological processing and repetition deficits (Tuomiranta et al., 2014b), spared orthographic learning ability can coexist with preserved repetition relying on phonology (Tuomiranta et al., 2014a). These studies provide evidence for a dissociation in word learning according to sensory modality and suggest that spared versus impaired input and output modalities should be considered in anomia therapy planning. Future research should corroborate these single-case findings and determine whether learning ability and treatment response via orthography vary across different degrees and patterns of dissociation between input and output modalities in word processing and learning.

### 4.2.4. Explicit word learning and long-term maintenance

Studies have also examined the long-term trajectory of newly acquired words after initial encoding, when no further training is available. Most studies indicate that novel linguistic information acquired via associative learning can be well-maintained 1 week after training as measured by receptive and expressive measures (Marshall et al., 1992, 2001; Tuomiranta et al., 2011), although decay in retrieval performance over time is more notable in PWA relative to healthy controls despite significant learning demonstrated immediately after training. Semantic and phonological cueing can aid PWA maintain their expressive learning performance for longer periods, ranging between 1 month (Freed and Marshall, 1995; Freed et al., 1995; Tuomiranta et al., 2011) and 6 months (Tuomiranta et al., 2012, 2014a). Also, written naming of newly learned words can show superior maintenance relative to oral naming

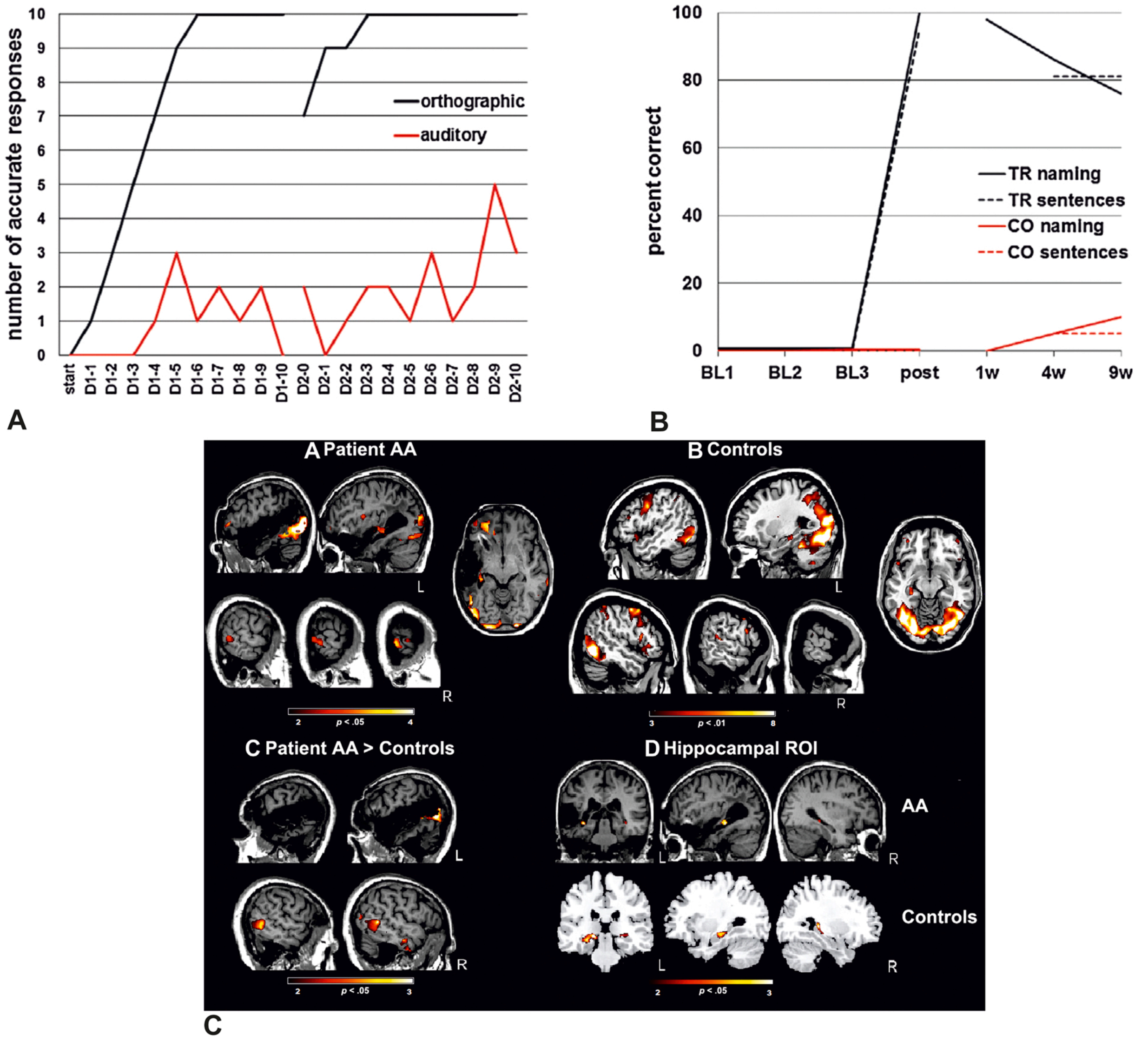

**Fig. 3.** Explicit associative novel word learning and vocabulary re-learning in aphasia. Behavioral and neuroimaging findings of patient AA (Tuomiranta et al., 2014b). (A) AA's new word learning ability impaired in the auditory modality and spared in the orthographic modality. (B) AA's re-learning performance from baseline (BL1, BL2, BL3) to post-therapy and follow-up assessments (1, 4, and 9 weeks) in naming and sentence production for trained (TR) and control (CO) items after vocabulary re-learning in the orthographic modality. (C) AA's brain correlates for word learning showing (a) main contrasts for AA with activations in the right hemisphere (middle occipital cortex, cuneus, middle temporal gyrus) and left middle frontal gyrus relative to (b) larger activations in healthy controls, (c) a contrast comparing AA and the healthy controls showing increased activations in the middle temporal gyrus for AA among other regions, and (d) her hippocampal recruitment during word learning. Reprinted from Cortex, 50 (2014), Tuomiranta et al., Hidden word learning capacity through orthography in aphasia, pp.154-191 Copyright © 2013 Elsevier Ltd. All rights reserved, with permission from Elsevier.

(Tuomiranta et al., 2014a, 2014b) remaining successful up to 6 months even without cueing (Tuomiranta et al., 2014b). Of note, the maintenance of novel expressive vocabulary may decline fast (Tuomiranta et al., 2014a, 2014b) and become challenging after encoding as its use is not often required for everyday communication (Tuomiranta et al., 2011). However, decay of long-term maintenance can occur even after intensive training in mild aphasia (Marshall et al., 1992), suggesting that successful maintenance of learned words requires regular access practice (Friedman et al., 2003).

### *4.2.5. The role of language and cognitive abilities on explicit word learning*

A few studies have provided evidence for a contribution of single word processing and verbal STM/WM abilities to explicit word learning in aphasia. The study conducted by Kroenke et al. (2013) found significant associations between lexical-semantic abilities and benefit from gesture-based expressive word learning, and between phonological processing abilities and expressive word learning via repetition without co-occurring gestures. In their study, lexical-semantic ability and phonological WM predicted this gesture-based benefit on novel word learning in PWA. Other studies have reported an association between lexical-semantic processing and learning of single novel word-referent pairings (Dignam et al., 2016). Moreover, single case studies have shown that PWA with more spared nonword repetition (which relies on phonological processing) and lexical-semantic processing also show better expressive new word learning and long-term maintenance relative to PWA with impaired lexical-semantic processing (Tuomiranta et al., 2011, 2012). These findings align with evidence of impaired verbal STM and expressive learning of nonwords and compound nouns (also relying on phonology and serial order) despite spared learning for familiar words and lexical-semantic properties reported in residual aphasia (Bormann et al., 2020).

The relationship between verbal STM and word learning in aphasia has been examined in more detail in a case series study conducted by Freedman and Martin (2001), who employed two paired-associate learning tasks to examine word learning in 5 PWA with phonological or semantic STM deficits and healthy controls. The phonological task required learning foreign word-pair associates (English familiar word - Spanish unfamiliar translation) whereas the lexical-semantic learning task required learning pairs of known English words and unfamiliar semantic definitions. Results showed that despite performing well on simple phonological and semantic processing tasks, PWA showed learning profiles in line with their verbal STM deficits. One patient with severe phonological STM deficit and better preserved semantic STM also demonstrated significantly better semantic than phonological learning, 3 PWA with greater deficits in semantic STM yet better preserved phonological STM showed better phonological than semantic learning, and one PWA who was severely affected in both types of verbal STM was impaired in both learning tasks. Similar to previous research on word list learning in PWA (Martin and Saffran, 1999), these results show that dissociable phonological and lexical-semantic components in verbal STM can independently contribute to the long-term learning of phonological and semantic material in aphasia.

In summary, both lexical-semantic abilities (Tuomiranta et al., 2011, 2012) and lexical-semantic STM (Freedman and Martin, 2001; Tuomiranta et al., 2012) are associated with receptive and expressive word learning in PWA, and lexical-semantic and phonological STM making independent contributions to this ability. Importantly, lexical-semantic abilities also predict response to anomia treatment (Dignam et al., 2016) and both lexical-semantic processing and STM are associated with response to repetition priming treatment for naming (Martin et al., 2006), suggesting that preserved access to semantics facilitates both word learning and re-learning in aphasia. Lexical-semantic processing may support word learning by facilitating the formation of associative connections between trained items (Martin and Saffran, 1999) and between words and supporting gestures (Kroenke et al., 2013), or connections with already existing long-term memory representations which may facilitate retrieval paths for recall (Ween et al., 1996). In-depth processing of semantic information may enhance the persistence and strength of memory traces (Craik and Lockhart, 1972) explaining the effectiveness of self-generated cues on word learning in aphasia (Freed and Marshall, 1995; Marshall et al., 1992, 2001), whereas impaired learning under impeded rehearsal underscores the contribution of rehearsal mechanisms in STM to word learning (Marshall et al., 1992).

### *4.2.6. Aphasia severity and explicit word learning*

Aphasia severity has been associated with expressive recall in word learning via phonological cueing but not with learning and long-term maintenance via self-cueing (Freed et al., 1995; Marshall et al., 2001), although it may constrain the ability to create detailed semantic personalized cues during learning (Freed and Marshall, 1995). Aphasia severity has been related to both learning ability for novel word-referent mappings and response to anomia therapy in PWA (Dignam et al., 2016), although single-case studies suggest that learning success and long-term maintenance can differ among PWA with similar severity profiles (Tuomiranta et al., 2011, 2012). Overall, the association between word learning and aphasia severity is confirmed by group studies (Dignam et al., 2016; Marshall et al., 2001) although the strength of this association may depend on the specific language and cognitive abilities required for successful performance in a given learning task. Further research should help in determining the consistency of this association across different learning paradigms and task requirements.

### *4.2.7. The role of clinical aphasic profile and lesion location on explicit word learning*

To date, no studies have systematically examined the relationship between clinical aphasic syndrome and explicit word learning. When considering the locus of language breakdown, it has been found that PWA with predominantly phonological impairment show successful word learning whereas PWA with semantic processing deficits predominantly show word learning deficits (Dignam et al., 2016). These results underscore the importance of characterizing processing deficits that may hinder effective word learning in aphasia.

With regard to lesion location, there is evidence that PWA with damage involving left inferior frontal regions and the anterior and mediotemporal gyri show more often reduced benefit from gesture-supported word learning (Kroenke et al., 2013). Neuroimaging studies have provided further insights about the brain regions that may support word learning in aphasia. Tuomiranta et al. (2014b) reported preserved ability to learn novel word-referent pairings and re-learn previously known vocabulary via orthography in a person with deep dysphasia resulting from an extensive left temporal lesion. The Diffusion Tensor Imaging (DTI) analysis revealed damage to the left arcuate fasciculus supporting phonological processing and learning (Hickok and Poeppel, 2007; Rodríguez-Fornells et al., 2009), with significant reductions in fractional anisotropy in the left superior and middle temporal, inferior parietal and inferior frontal gyri relative to a control group. An fMRI experiment for reading words and pseudowords showed increased activation in spared occipital and frontal left hemisphere regions and extensive right hemisphere activation in this participant, in contrast to a strongly large left-lateralized brain network for controls. The fMRI experiment for word learning via orthography showed increased bilateral activation in the hippocampus, and right hemisphere activation in temporo-frontal regions relative to controls, with the opposite contrast revealing increased activation in the superior temporal gyrus (damaged in this patient) and the right temporo-frontal regions (Fig. 3 C). This study supports the notion of the hippocampus being a critical region for associative word learning in aphasia (Davis and Gaskell, 2009; Rodríguez-Fornells et al., 2009; Ullman, 2001, 2004). The study conducted by Coran et al. (2020) examining associative novel word learning ability in 3 PWA also characterized their white matter connectivity. The authors found that the patient with the most preserved left arcuate fasciculus (especially temporo-parietal connections) and inferior longitudinal fasciculus showed fully successful receptive learning and better (albeit minimal) expressive learning relative to the other two patients. The second patient with better preservation of ventral pathways also showed successful receptive learning although his expressive learning was at floor levels. In turn, the patient with the largest damage to the left arcuate fasciculus and severe ventral pathway disconnection showed impaired receptive and expressive learning. These findings suggest that greater integrity of the left dorsal and ventral white matter pathways may support word learning in aphasia more effectively. Group-level lesion-symptom mapping approaches combined with fMRI could provide important insights into the critical brain regions that sustain word learning in PWA.

#### 4.2.8. *Linguistic versus non-linguistic explicit learning*

Another focus of growing research interest is whether reduced learning ability in some PWA reflects language-specific or domain-general deficits. A recent study addressing verbal and nonverbal explicit learning in aphasia found that PWA present superior learning ability for noun pairs versus complex visual scene pairs (Wang et al., 2020). As suggested by the authors, it is possible that linguistic learning may be facilitated by spared semantic processing of single familiar words whereas learning visual associations may require more complex semantic verbal mediation or that visual associations pose greater WM load relative to real words (Christensen and Wright, 2010). More studies are needed to address questions about the domain-specific or domain-general nature of learning ability in aphasia and to elucidate the factors that drive differences across linguistic and non-linguistic learning.

### 4.3. *Implicit language learning in aphasia*

Implicit learning has been defined as the process by which learners develop knowledge about the underlying structure of rule-governed complex stimulus environment (Reber, 1967, 1989). Implicit knowledge is acquired incidentally (Ullman, 2001, 2004), it entails abstract representations of the structure extracted from perceptual input (Reber, 1989) and occurs via exposure or performance in the absence of awareness, without instruction, intention or conscious reflective strategies to learn (Batterink et al., 2019; Reber, 1989). Implicit learning is thought to contribute to the acquisition of motor, perceptual, cognitive and language skills (Williams, 2020) and support both early language acquisition and language learning in adults (Rodríguez-Fornells et al., 2009). With these considerations in mind, this section reviews studies examining language learning (i.e., learning of novel words, word-referent mappings and sequences of lexical and sub-lexical items) using traditional experimental paradigms that largely conform to the abovementioned characteristics of implicit learning (see Table 2 for a summary of these studies and their most relevant findings).

**Table 2**
Studies of implicit language learning in aphasia.

| Study | Participants | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| Goschke et al. (2001) | *Exp. 1:* 5 PWBA, 5 PWWA and 2 groups of 5 HC.<br>*Exp. 2:* 5 PWBA (3 included in exp. 1), 5 trained HC, and 10 untrained HC. | *Exp. 1:* a 10-trial viso-motor response sequence.<br>*Exp. 2:* an 8-trial viso-motor response sequence (condition 1), and an 8-trial phoneme sequence (condition 2). | *Design exp. 1:* SRTT tapping learning of a repeating structured sequence of motor responses matching the location of an asterisk among 4 locations.<br>*Duration:* 1 session.<br>*Design exp. 2:* A phoneme SST that required a motor response matching the visual location of a spoken phoneme among 4 possitions. Involved learning a structured sequence of motor responses to a random order of spoken phonemes (condition 1) or learning a structured sequence of spoken phonemes with a random order of visual location and motor responses (condition 2).<br>*Duration:* 1 session (1 year apart from exp. 1) | -*Exp. 1:* RT cost for switching from a structured to a random sequence.<br>-Recognition test: identifying sequence fragments as old/new.<br>-Prediction task: identifying the location for the next stimulus of a sequence (measures explicit knowledge).<br>-*Exp. 2:* RT cost for each condition separately.<br>-Reproduction of motor sequences manually and phoneme sequences verbally (measures of explicit knowledge). | - *Exp. 1:* all groups showed significant RT cost during learning.<br>-No evidence of explicit knowledge of the motor sequence for any group.<br>-*Exp. 2:* HC learned both the motor and phoneme sequence.<br>-PWBA learned the motor sequence but were selectively impaired in phoneme sequence learning.<br>-None of the groups showed explicit sequence knowledge relative to the untrained HC.<br>-One PWBA showed explicit knowledge of the full phoneme sequence despite impaired phoneme learning (minimal RT cost). | -Frontal lesions/ Broca's aphasia present selectively impaired phoneme sequential learning but not motor sequence learning. |
| Dominey et al. (2003) | *Exp. 1:* 7 PWA with agrammatism. *Exp. 2:* 2 PWA with agrammatism. | *Exp. 1:* 10 letter sequences from an abstract non-canonical structure 123–213 and a canonical structure 123–123.<br>*Exp. 2:* serial and abstract structured sequences of visual letters. | *Design exp. 1:* abstract non-canonical and canonical structure grammar learning task with exposure to both structures followed by a classification task.<br>*Duration:* NR.<br>*Design exp. 2:* visual SRTT involving serial and abstract structures.<br>*Duration:* NR. | -*Exp. 1:* clasification of 20 new letter strings as similar or not similar to trained structure.<br>- *Exp. 2:* RT cost (measure of serial structure learning).<br>-RT reduction for unpredictable versus non-predictable elements within a new sequence with the same abstract structure (measure of abstract structure learning). | -*Exp. 1:* selectively impaired classification of new strings in the non-canonical structure relative to the canonical structure.<br>-*Exp. 2:* significant serial learning structure but impaired learning for abstract structure (confirmed by analyses at the individual level) relative to significant learning of serial and abstract structure in HC. | *Exp. 1:* non-canonical sequence classification associated with syntactic comprehension. |
| Schuchard and | | 2 sets of four spoken nouns and their | *Design:* SST including an 8-item sequence | -RT cost for switching from a structured to a | *Implicit learning condition:* | -No differences in learning between PWA with high |

(*continued on next page*)

**Table 2** (*continued*)

| Study | Participants | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| Thompson (2014) | 10 PWA with agramatism and 18 HC | pictures combined into an 8-item sequence (one set per condition). | that required a motor response matching the visual location of each spoken noun among 4 possitions across an implicit and explicit condition.<br>The implicit condition was completed first with no instruction about the existence of a sequence (which was informed in the explicit condition).<br>*Duration:* 1 session for each condition (1–3 days apart). | random sequence.<br>-Word prediction test: identifying the picture for the next word of a sequence (measures explicit knowledge).<br>-Self-report of the 8-item sequence. | -PWA and HC showed significant RT cost during learning.<br>- HC but not PWA showed significant learning on the word prediction test.<br>-5 HC and 1 PWA reported 2–4 words of the sequence.<br>*Explicit learning condition:*<br>-HC but not PWA showed significant RT cost during learning.<br>- HC but not PWA showed significant learning on the word prediction test.<br>-14 HC recalled 2–8 words of the sequence and 1 PWA recalled 4 words. | and low auditory comprehension or high and low naming.<br>-The HC outperformed PWA in a listening sentence span task, however, a direct association between working memory and learning ability in PWA was not examined. |
| Peñaloza et al. (2015) | 14 PWA, 14 older HC and 120 young HC (recruited for task validation) | An artificial language made of 4 trisyllabic pseudowords. | *Design:* Speech segmentation via SL. Passive listening to the nonsense artificial language with transitional probabilities between syllables (higher within words and lower at word boundaries) as the only cue to segment words from speech.<br>*Duration:* 1 session. | 2-alternative forced choice test: recognition of words from the language from nonwords made of syllables included but never concatenated together in the language. | -Learning below young and older HC.<br>-Significantly above chance learning performance, comparable to the older HC.<br>-Four PWA with significant learning above chance level. | -Aphasia severity was not associated with SL, but it correlated with word pointing span (verbal STM).<br>-PWA with posterior lesions showed better SL and verbal STM relative to PWA with anterior lesions.<br>-PWA with inferior frontal lesions showed impaired learning and worse verbal STM. |
| Peñaloza et al. (2017) | 16 PWA, 18 older HC and 39 young HC (recruited for task validation). | CSL task: 9 novel word- novel referent (tools[a]).<br>SL task: artificial language made of 4 trisyllabic pseudowords. | *Design:* CSL task: learning of word-referent mappings under referential ambiguity (two objects and two spoken words per trial) to discover correct word-referent pairings without feedback.<br>SL task: pasive exposure to an artificial language to discover word boundaries in connected speech.<br>*Duration:* 2 sessions. | -CSL task: 4 4-alternative forced-choice word-picture matching tests (test 1 measured pure CSL, tests 1–4 measured learning trajectories over time).<br>-SL task: 2-alternative forced choice test for recognition of words from the language versus nonwords. | -All groups showed significant CSL (test 1), although learning for PWA was slower and below HC.<br>-7 PWA showed significant CSL (test 1) and 9 PWA showed significant incremental learning (test 1–4).<br>-All groups showed significant SL, although PWA were below the HC.<br>-3 PWA showed significant SL.<br>-A strong association between CSL and SL was found for all 3 groups. | -Aphasia severity was associated with CSL (test 1).<br>-Phon. processing and verbal STM predicted CSL (test 1), but became non-significant after controlling for aphasia severity.<br>-Phon. and lex-sem. STM were independently associated with CSL (test 1) for the older HC. |
| Schuchard and Thompson (2017a) | 12 PWA with agrammatism, 12 trained HC 12 untrained HC who only completed testing. | 50 spoken grammatical sentences of a nonsense language made of 10 monosyllabic pseudowords, across five lexical categories. | *Design:* AGL task with exposure to 50 sentences of 3–5 pseudowords organized following the rules of a hierarchical phrase structure grammar.<br>Sentences were presented while watching a muted nature video.<br>*Duration:* 2 training/test sessions. | -3 artificial grammar judgment tests of trained and untrained grammatical and agramatical sentences (deciding whether sentences followed or not same word order rules as in training) completed after training on session 1, before and after training on session 2. | -Learning in PWA did not differ from trained HC and both were superior to untrained HC.<br>-Only the trained HC showed increased learning across 3 tests.<br>-Test performance was higher for gramatical relative to agramatical items only for trained HC. | -Averaged learning performance was not associated with syntactic impairment in comprehension, production of gramatical sentences or with overall aphasia severity in PWA. |
| Cope et al. (2017) | 10 PPPA, 10 PWA due to stroke, and 11 HC | Two artificial grammars comprising sequences of | *Design:* 2 AGL tasks involving non-sense words or tones, with 8 | -AGL tasks: recognition tests on correct sequences (following the rules of the | -Both patient groups showed learning performance below the | -AGL was not associated with general non-verbal cognitive ability or |

(*continued on next page*)

**Table 2** (*continued*)

| Study | Participants | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| | | monosyllabic nonsense words and tones across 8 unique elements. | stimuli types arranged into sequences according to increasingly complex rules. The exp. included 3 rounds of exposure, testing and feedback per modality alternating modalities, a final language exposure and a control oddball task. The oddball task involved novel unheard oddball items at locations where an ordering violation would occur in an incorrect sequence.<br>*Duration:* 1 session. | artificial grammar), and incorrect sequences (violating the rules of the artificial grammar).<br>-control oddball task: recognition of oddball nonwords (incorrect nonword sequences). | HC, in particular PWA with worse learning of the language grammar.<br>-Additional exposure improved learning in patients on the language sequence with only marginal improvement for the tone sequence.<br>-Learning was better for linear rules (serial orderings) versus complex rules (non-adjacent orderings) in all groups.<br>-All groups showed similar response patterns within each task, but performance differed for nonsense words and tones despite similar grammar structures.<br>-All groups showed high performance on the oddball task. | sentence comprehension in patients.<br>-Aphasia severity predicted linguist AGL (linear rules).<br>-Diagnosis predicted tone AGL (PPPA worse than PWA).<br>- In PWA putamen lesions predicted linguistic AGL, and larger lesions were associated with worse oddball performance (improved with anterior lesion distribution).<br>-In PPPA, age and left frontal grey matter volume were associated with better linguistic AGL. |

PWA = people with aphasia; PWBA = people/person with Broca's aphasia; PWWA = people/person with Wernicke's aphasia; PPWA = people with non-fluent primary progressive aphasia; HC = healthy controls; NR = not reported; Exp. = experiment; Phon. = phonological; Lex-sem. = lexical-semantic; STM = short-term memory; SRTT = serial reaction time task; SST = serial search task; RT = reaction time; AGL = artificial grammar learning; SL = statistical learning; CSL = cross-situational learning.

[a] Tools from the "Ancient Farming Equipment" (AFE) paradigm (Laine and Salmelin, 2010).

### 4.3.1. *Sequential learning*

Studies of sequential language learning have employed the Serial Reaction Time Task paradigm (SRTT, Nissen and Bullemer, 1987) in which learners generate a rapid motor response to indicate the location of visual cues appearing in one of four locations. Unknown to them, visual cues are arranged in repeating sequences in sequential trials or in non-repeating sequences in random trials. As reaction times (RTs) decrease over time during practice with a repeating sequence across trials and increase when switching to random trials, the RT cost observed when switching from the structured to the random sequence is a reliable indicator of online procedural sequential learning.

Using this approach, Goschke et al. (2001) (experiment 1) found that people with Broca's and Wernicke's aphasia demonstrated spatial-motor sequence learning in SRTT comparable to healthy controls despite no evidence of explicit learning on a recognition test and a sequence prediction task. In experiment 2, the authors further compared phoneme sequence learning in people with Broca's aphasia and healthy controls in two conditions. Four letters were presented along four possible locations and required a key press corresponding to a spoken phoneme's location which changed across trials. In the motor response sequence condition, the spatial locations of the spoken target phonemes formed a repeated pattern across trials while the spoken phonemes were presented in a random order. In the spoken phoneme sequence condition, the spoken target phonemes were presented in a repeating sequence while the motor responses across trials followed a random order. Only the healthy controls learned both sequences, whereas participants with Broca's aphasia learned only the motor sequence and had selective difficulty learning the phoneme sequence. None of the groups showed explicit sequence knowledge (although one patient could reproduce the entire phoneme sequence despite showing a small RT cost). A similar study conducted by Dominey et al. (2003) used a visual letter SRTT to examine learning for serial structures (serial order of elements in a sequence) and abstract structures (rules for relations of elements in a sequence) in 2 PWA with agrammatism and healthy controls. Results showed that serial structure learning was largely spared for PWA and controls. However, PWA showed impaired learning for abstract structures while healthy controls showed significant transfer to predictable sequences and RT reduction for predictable versus non-predictable sequences.

Another study by Schuchard and Thompson (2014) examined sequential learning in people with agrammatic aphasia and healthy controls using a Serial Search Task. Participants were presented with a spoken word together with four pictures and indicated the corresponding picture location by a key press. In the implicit learning condition with no knowledge of the underlying sequence, both PWA and controls demonstrated significant learning as per diminishing RT cost, but only the controls showed above chance knowledge of trained sequences in a word prediction test. In the explicit learning condition where the participants were informed of the repeating sequence, only the healthy controls showed learning as measured by the RT cost and significantly above chance sequence knowledge on the word prediction test, while PWA performed below chance.

Overall, findings regarding sequential language learning in aphasia are inconsistent across studies. Although impaired phoneme sequence learning has been found in Broca's aphasia (Goschke et al., 2001), spared learning of letter sequences and serial structures has also been reported in agrammatic patients (Dominey et al., 2003). Moreover, PWA with agrammatism can show significant sequential learning for words under implicit conditions (Schuchard and Thompson, 2014). Divergent findings across studies may reflect differences in task difficulty and stimulus processing requirements since agrammatic patients may more easily rely on semantic processing for picture sequences of real words (Schuchard and Thompson, 2014) relative to auditory sequences of sublexical elements (Goschke et al., 2001). Of note, the dissociation between spatio-motor and phoneme sequential learning in frontal lesions (Goschke et al., 2001) suggests that implicit learning of different sequence types and modalities may be supported by partially separable brain systems (Frost et al., 2015).

### 4.3.2. *Statistical learning*

Statistical learning (SL) is a cognitive mechanism that enables learners to discover and extract the underlying regularities from sensory input (Frost et al., 2015). SL can contribute to the acquisition of novel linguistic information by computing the statistical relationships between adjacent dependencies in a novel speech stream (Williams, 2020) and the co-occurrence between words and meanings across multiple learning instances (Yu and Smith, 2007). Two studies have examined linguistic SL in aphasia. Peñaloza et al. (2015) examined the ability to segment novel words from fluent speech via SL in PWA and healthy controls. All participants were exposed to a continuous spoken artificial language formed by pseudowords in which transitional probabilities between syllables were the only reliable cue to detect word boundaries (higher for syllables within pseudowords and lower for syllables spanning pseudoword boundaries). Results showed that both the aphasia and healthy control group achieved comparable and significantly above-chance SL on a 2-alternative forced-choice test measuring the ability to identify pseudowords from the artificial language from nonwords (syllables presented but never concatenated in the language) (Fig. 4 A). A follow-up study conducted by Peñaloza et al. (2017) examined cross-situational learning (CSL) in PWA and a healthy control group and assessed its relationship with SL in the speech segmentation task previously reported (Peñaloza et al., 2015). In the CSL task, each learning trial was referentially ambiguous with 2 spoken pseudowords and 2 novel visual referents (4 possible word-referent associations). Participants could resolve referential ambiguity and learn the correct mappings by tracking the co-occurrence between words and referents across trials. All groups demonstrated significant CSL. Although PWA showed slower and worse learning relative to the healthy controls, 7 PWA demonstrated learning on the first recognition test and 9 on the last test measuring cumulative learning. The study also revealed a significant association between CSL and SL in all groups, suggesting a common learning mechanism for words and word-referent mappings in aphasia. These findings suggest SL as a mechanism that can remain preserved is some PWA supporting both the learning of novel word phonology (Peñaloza et al., 2015) and word-referent mappings representing basic lexical-semantic associations (Peñaloza et al., 2017) via bottom-up processing of statistical co-occurrences in a novel language learning context.

### 4.3.3. *Artificial grammar learning*

Other studies have examined learning ability using the artificial grammar learning (AGL) paradigm (Reber, 1967). In its most traditional form, this paradigm requires learning elements from a structured grammar according to specific rules via exposure, and to categorize new strings as grammatical or ungrammatical on the basis of the previously exposed rules. Using this paradigm, Dominey et al. (2003) compared the ability of PWA with agrammatism to learn simple versus complex non-canonical abstract structure of letter sequences. Their results showed a selective impairment that only affected AGL for non-canonical complex sequences in agrammatic aphasia. More recently, Schuchard and Thompson, 2017 examined AGL in PWA with agrammatism and healthy controls on a task that involved the exposure to monosyllabic pseudoword-based grammatical sentences while watching a muted nature video. Participants were unaware of the rules of the hierarchical phrase structure grammar governing item ordering in the language. Both trained groups showed comparable accuracy and outperformed an untrained control group on an artificial grammar judgment test. However, only the trained control group but not the aphasia group showed significant increase in performance across repeated testing. Another study conducted by Cope et al. (2017) compared AGL ability for linguistic and non-linguistic auditory sequences in non-fluent PWA, people with non-fluent primary progressive aphasia (PPPA) and healthy controls. The task involved three alternating exposures to pseudoword and tone artificial grammars, each one followed by a test that required deciding whether test sequences were consistent or not with the rules used during exposure. Pseudoword and tone sequences of variable length were ordered in the artificial grammars according to linear, complex configurational or hierarchical rules. Results showed that pseudoword sequence learning was impaired for both patient groups and significantly worse for PWA relative to controls, although all groups improved learning with additional exposure across all rule types. All groups showed better pseudoword learning for simple linear rules relative to complex configurational and hierarchical rules. Tone sequence learning was worse for patients with PPPA, while PWA did not differ from controls or PPPA. Additional tone sequence exposure led to only marginal improvements for all groups and their performance was worse for complex configurational rules relative to both linear and

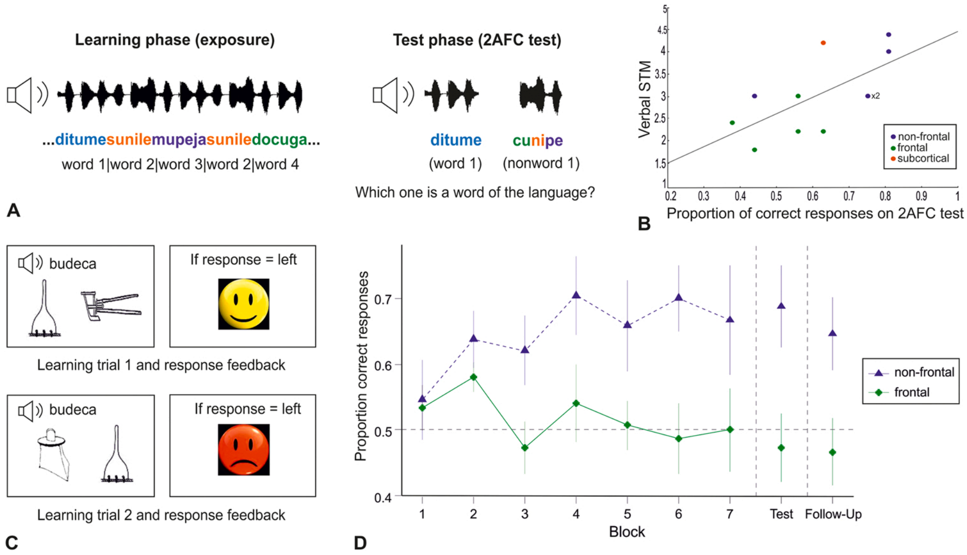

**Fig. 4.** Implicit and incidental learning in aphasia. Panels A-B depict speech segmentation via statistical learning in aphasia (Peñaloza et al., 2015). (A) Task design with exposure to an auditory pseudoword-based artificial language in which transitional probabilities are the only cue to discover word boundaries and a 2-alternative forced-choice (2AFC) test that requires the identification of words of the language versus nonwords. (B) Association between statistical learning and verbal short-term memory (STM) in aphasia, showing that PWA with frontal lesions present both verbal STM and statistical learning deficits. Panels C-D show a study of incidental word learning under referential ambiguity in aphasia (Peñaloza et al., 2016). (C) The learning task required figuring out the correct word-referent associations between a spoken pseudoword and two possible referents in each learning trial followed by accuracy-based feedback. (D) Lesion location effects on novel word learning showing near-healthy control performance for PWA with posterior lesions and impaired performance for PWA with frontal lesions during online learning (training blocks 1–7), the immediate and 1 week follow-up tests.

hierarchical rules. Notably, a hierarchical cluster analysis revealed similar response patterns across groups in each task, although performance was different for nonsense words and tones reflecting different learning approaches even when the tasks entailed similar artificial grammar structures.

To summarize, studies provide mixed evidence for spared (Dominey et al., 2003; Schuchard and Thompson, 2017) but also impaired (Cope et al., 2017; Dominey et al., 2003) AGL in the linguistic domain in PWA with agrammatism. Studies converge in that AGL for simple adjacent sequence structures of letters or pseudowords can be largely preserved in agrammatic aphasia, whereas AGL for non-adjacent complex sequences is more affected (Cope et al., 2017; Dominey et al., 2003). Learning performance in some agrammatic patients can improve with further training (Cope et al., 2017) although others may show limited benefit from additional exposure (Schuchard and Thompson, 2017), suggesting the possibility of differential severity effects across samples or different degrees of difficulty in the structure of the grammars employed across studies. Thus, knowledge on the factors that influence differences in AGL performance for simple adjacent and complex non-adjacent structured sequences in aphasia is still too limited.

#### 4.3.4. *The role of language and cognitive abilities in implicit language learning*

A few studies have also provided important evidence about possible interactions between implicit language learning and other cognitive abilities. For instance, AGL performance was not associated with general non-verbal cognitive ability in PWA and PPPA (Cope et al., 2017). SL has been related to verbal STM in PWA in speech segmentation tasks (Peñaloza et al., 2015), although this association has been confounded with aphasia severity on CSL tasks (Peñaloza et al., 2017). Notably, phonological and lexical-semantic STM differentially modulate word learning under referential ambiguity in CSL in healthy adults, suggesting independent verbal STM contributions to word learning (Peñaloza et al., 2017). While implicit language learning and language processing ability has been linked in healthy adults (see Arciuli and Torkildsen, 2012, for a review), this relationship is far from clear in aphasia. Phonological processing has been associated with CSL in aphasia but not when factoring out aphasia severity (Peñaloza et al., 2017). Also, PWA with agrammatism with high versus low auditory comprehension or high versus low naming performance do not significantly differ in their sequential language learning ability (Schuchard and Thompson, 2014). Further, while AGL for complex abstract structures has been associated with syntactic comprehension in agrammatic aphasia (Dominey et al., 2003), other studies have found no significant associations between AGL and syntactic ability in comprehension (Cope et al., 2017; Schuchard and Thompson, 2014, 2017) or in production (Schuchard and Thompson, 2017) in agrammatism. This may suggest separate neural mechanisms for syntactic processing and sequential learning (Schuchard and Thompson, 2017). More research is needed to identify the aspects of cognition that support implicit learning in aphasia, and to clarify the association between implicit language learning and processing in aphasic and healthy speakers. Future studies should determine if these associations indicate general language and cognitive contributions to implicit language learning or if they rather reflect higher reliance on compensatory language and cognitive resources after brain damage.

#### 4.3.5. *Aphasia severity and implicit language learning*

Studies examining the association between learning ability and aphasia severity have yielded equally mixed findings. Some studies have shown no significant associations between aphasia severity and SL in speech segmentation tasks in PWA (Peñaloza et al., 2015) and overall AGL in agrammatic aphasia (Cope et al., 2017; Schuchard and Thompson, 2017). However, this association has been reported for SL in CSL tasks (Peñaloza et al., 2017) and in AGL involving linear rules of pseudoword sequences (Cope et al., 2017). Future research with larger samples will need to clarify whether these findings reflect the effects of specific deficits in language processing relevant to specific aspects of language learning and if they only emerge under cognitively taxing learning task requirements.

#### 4.3.6. *The role of clinical aphasic profile and lesion location on implicit language learning*

Implicit language learning has also been studied in PWA as a function of clinical aphasic profile (i.e., Broca's aphasia and agrammatism) denoting the classical division of anterior/ posterior damage. Taking this approach, studies have found impaired speech segmentation via SL in PWA with inferior frontal lesions relative to non-frontal lesions (Peñaloza et al., 2015), as well as impaired phoneme and letter sequential learning (Dominey et al., 2003; Goschke et al., 2001) and impaired AGL for complex abstract structures (Dominey et al., 2003) in Broca's aphasia. Further, putaminal lesions predict linguistic AGL in PWA with agrammatism (Cope et al., 2017). These results support the view of the DP model regarding the role of the inferior frontal regions and the basal ganglia in implicit language learning (Ullman, 2001, 2004). However, other studies have revealed that PWA with agrammatism can demonstrate AGL for pseudowords (Schuchard and Thompson, 2017) and sequential learning for real words (Schuchard and Thompson, 2014) and letters in simple serial structures (Dominey et al., 2003). This suggests that the integrity of learning ability may depend on language structure or processing complexity. As indicated earlier, it is also possible that spared sequential word learning can be supported by other spared abilities (e.g., visual receptive lexical-semantic knowledge during sequential learning with pictured words, in Schuchard and Thompson, 2014).

It is worth considering the role of lesion location on language learning as it relates to STM/WM in aphasia. In line with existing language-based accounts of STM/WM involving a phonological and semantic component (see Martin, 2005 for a review), evidence suggests that verbal STM contributes to SL in PWA (Peñaloza et al., 2015) (Fig. 4B) and phonological and lexical-semantic STM make independent contributions to CSL in healthy adults (Peñaloza et al., 2017). However, since inferior frontal regions contribute to both phonological and semantic STM/WM (Martin et al., 2021), it remains unclear whether implicit learning deficits associated with left frontal damage in PWA result from lesions that directly disrupt the underlying learning mechanism such as SL, indirectly disrupt learning performance via impairment to specific STM/WM abilities supporting learning, or both. In fact, there is evidence that PWA with posterior lesions demonstrate both better SL ability and lexical-semantic verbal STM relative to PWA with anterior lesions who show impaired learning and worse verbal STM (Peñaloza et al., 2015). Altogether, these findings suggest that verbal STM capacity and the integrity of the left inferior frontal region are crucial for language learning in aphasia, however, future mediation analyses with larger samples that enable sufficient statistical power may make it possible to disentangle independent contributions of lesion location and cognitive capacities to implicit language learning in this population.

#### 4.3.7. *Linguistic versus non-linguistic implicit learning*

Only two studies have directly compared implicit linguistic and non-linguistic learning in PWA, yielding contradictory evidence. While the dissociation between phoneme and motor sequential learning in agrammatic aphasia suggests domain-specific deficits related to clinical/ anatomical profile (Goschke et al., 2001), there is also evidence for domain-general deficits in AGL for pseudoword and tone sequences in this population (Cope et al., 2017). As commented earlier, there is supporting evidence for both impaired (Dominey et al., 2003) and largely spared (Dominey et al., 2003; Schuchard and Thompson, 2014, 2017) implicit language learning in aphasia, and evidence for preserved non-linguistic sequential learning (Goschke et al., 2001) has been recently corroborated (Schuchard et al., 2017b). Other studies examining only non-linguistic implicit learning in aphasia have reported impaired or atypical performance in visual AGL tasks in agrammatic aphasia (Christiansen et al., 2010; Zimmerer et al., 2014) while non-agrammatic patients show within-normative-range AGL performance (Zimmerer et al., 2014). In addition, although learning deficits seem to be present particularly in PWA with anterior frontal lesions and in the related profile of agrammatism, implicit learning deficits are not always observed after frontal damage. For instance, impaired SL in the linguistic domain has been reported in PWA with frontal versus non-frontal lesions (Peñaloza et al., 2015), yet other studies have found significant visual SL in PWA with frontal lesions with comparable performance to those with posterior lesions (Vadinova et al., 2020). Moreover, PWA with left frontal lesions show spared AGL for pitch sequences comparable to healthy controls as evidenced by event-related potentials showing larger early negativity in response to ungrammatical relative to grammatical pitch sequence events (Jarret et al., 2019).

To summarize, although evidence for impaired learning in agrammatic aphasia supports theoretical accounts for implicit language learning as relying on the fronto-basal procedural memory system (Ullman et al., 2004), findings do not conclusively support a unitary domain-general implicit learning system in aphasia. Domain-specificity for implicit learning is supported by the presence of dissociations in learning for specific types of structures (Goschke et al., 2001), and the finding that both aphasic and healthy speakers employ different approaches to linguistic versus non-linguistic artificial grammars despite similar sequence structures (Cope et al., 2017). This suggests that partially separable neural systems may support implicit learning ability for linguistic and non-linguistic structures (Goschke et al., 2001). In addition, although the left inferior frontal regions may be important for particular forms of linguistic implicit learning such as SL (Peñaloza et al., 2015), this region may not play an equally exclusive or dominant role on all forms of implicit learning, particularly for non-linguistic SL (Jarret et al., 2019; Vadinova et al., 2020). Importantly, although evidence as to whether deficits in implicit learning in aphasia are domain-general or domain-specific is inconclusive and remains an open question for future research, it is worth considering that domain-specific and domain-general views may not be mutually exclusive. It is possible that domain-general regions contribute to general computation principles operating across different domains or modalities which interact with brain regions underlying domain-specific representation, depending on the input and output modalities on which learning actively operates at the moment (Goschke et al., 2001; Frost et al., 2015). Again, further studies are needed to clarify the variability in learning performance across linguistic and non-linguistic paradigms of implicit learning across different clinical and lesion profiles in aphasia.

### 4.4. *Incidental language learning in aphasia*

Incidental language learning entails the learning of vocabulary as the by-product of engaging in a task or activity not explicitly geared to vocabulary learning. While the acquisition of knowledge is unconscious, unplanned or unintentional as in implicit learning (Ullman, 2001, 2004), such acquired knowledge is not expected to remain largely inaccessible to conscious awareness (Kelly, 2012). This section reviews studies that employ learning paradigms that conform to the concept of

**Table 3**
Studies of incidental language learning in aphasia.

| Study | Participants | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| Grossman and Carey (1987) | 15 PWA (8 PWBA and 7 PWWA) | 1 novel adjective word “bice” (dark green). | *Design:* incidental learning with passive exposure to target word during a drawing task.<br>*Duration:* 1session for training and testing, and 1 follow-up testing session 2 weeks apart (5 PWBA and 4 PWWA). | -Grammatical judgment task (identify trained word as an adjective or verb in sentences).<br>-Object classification task (classify objects as bice or non-bice along color and shape dimensions).<br>-Naming, object classification and sentence production at 2 weeks follow-up. | -Lower accuracy and slower learning for PWA relative to HC.<br>-Superior learning for PWWA relative to PWBA on grammatical judgments (closer to HC).<br>-PWBA could classify new objects influenced by shape not color.<br>-PWWA showed worse semantic object classification but only color influenced their classification.<br>-PWWA were better at object classification and sentence production relative to PWBA at follow-up.<br>-2 PWWA had accurate naming at follow-up. | Learning difficulty in accordance with aphasic syndrome: impaired grammatical learning in PWBA and impaired semantic learning in PWWA. |
| Koul and Lloyd (1998) | 10 PWA, 8 people with right hemisphere damage and 10 HC | 40 Blissymbols (4 categories combining high and low transluciency and complexity) and 120 foil pictures. | *Design:* associative learning of symbol-label pairings (word-referent matching task involving a spoken word and identification of target symbol among 7 foils).<br>*Duration*: 2 sessions. | -Accuracy in word-symbol matching over training.<br>-Accuracy on a retention test at 1 week. | -PWA but not people with right hemisphere damage showed comparable learning to the HC.<br>-All 3 groups showed better recognition performance at 1 week relative to immediate learning performance. | Symbol transluciency but not visual complexity modulated recognition of trained mappings in all 3 groups. |

(*continued on next page*)

**Table 3** (*continued*)

| Study | Participants | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| Breitenstein et al. (2004) | 1 PWBA (FR), 1PWWA (RH) and 38 HC | 50 nonword-familiar object picture pairs. | *Design:* probabilistic learning with referential ambiguity across trials (higher co-occurrence for correct versus incorrect word-object pairings) to discover correct word-referent pairings. Feedback provided only for half of the HC. *Duration:* 5 training sessions for HC, 1 training session for RH and FR, and 1 follow-up training/ test session for FR 10 months after. | -Judgment of the accuracy of word-referent pairings presented during training (HC and PWA) and reaction times (HC).<br>-Transfer test after training (judgment of the accuracy of trained nonword- real label of trained picture pairings reflecting word meaning knowledge). | -HC showed increasingly faster learning during training and successful transfer and long-term retention. Steeper learning curves were observed in the group receiving feedback.<br>-PWA were slower and less accurate in learning compared to HC.<br>-Above chance performance during training (RH and FR) and on the transfer test (FR).<br>-FR retained performance after retraining at 10 months follow-up. | Both PWA showed significant learning regardless of aphasic profile (Broca's versus Wernicke's aphasia). |
| Peñaloza et al. (2016) | 14 PWA, 14 older HC and 45 young HC (recruited for task validation). | 6 trisyllabic pseudoword-unfamiliar object pairings (tools[a]). | *Design:* learning of word-referent mappings under referential ambiguity (two objects and one spoken word per trial) to discover correct word-referent pairings with visual feedback. *Duration:* 1 session for learning and immediate testing and 1 testing session 1 week apart. | -Performance during learning with feedback.<br>-Immediate recognition test without feedback.<br>-1 week follow-up recognition test without feedback. | -PWA were slower and less accurate in learning relative to the older and young HC.<br>-All groups showed only minimal decreases in recognition performance at 1 week.<br>-PWA showed significantly above chance learning on the immediate and follow-up recognition tests.<br>-5 PWA showed significant learning above chance on the immediate test and 4 PWA on the follow-up test. | -Aphasia severity modulated learning rate.<br>-Phon., lex-sem. processing and verbal STM predicted immediate and follow-up recognition performance, but only verbal STM predicted immediate but not follow-up recognition after controlling for aphasia severity.<br>-PWA with frontal lesions showed impaired learning and worse performance than PWA with non-frontal lesions during learning and on recognition tests (lesion effects reduced by controlling for verbal STM). |

PWA = people with aphasia; PWBA = people/person with Broca's aphasia; PWWA = people/person with Wernicke's aphasia; HC = healthy controls; Phon. = phonological; Lex-sem. = lexical-semantic; STM = short-term memory.

[a] Tools from the "Ancient Farming Equipment" (AFE) paradigm (Laine and Salmelin, 2010).

incidental learning and do not represent classical learning paradigms of implicit learning (see Table 3 for study details).

The study conducted by Grossman and Carey (1987) examined the ability to learn semantic and grammatical information about novel words via incidental exposure in Broca's and Wernicke's aphasia. PWA and healthy controls were exposed to a color adjective pseudoword and were required to make drawings with the referred color pen while being unaware of the word meaning and uninstructed to learn the word properties. PWA were slower and less accurate in learning the word meaning relative to controls. Broca's aphasia patients showed difficulty identifying the word's grammatical form class (verb versus adjective) on a grammatical judgment task and were outperformed by Wernicke's aphasia patients who were almost on par with the healthy controls. Conversely, Broca's aphasia patients outperformed Wernicke's aphasia patients in classifying colored objects in a semantic object classification task. Successful naming and object pointing performance was observed only in Wernicke's but not in Broca's aphasia.

Other studies have addressed the referential ambiguity in learning novel word-referent mappings proposed by the INM framework (Rodríguez-Fornells et al., 2009) using associative (Koul and Lloyd, 1998), probabilistic (Breitenstein et al., 2004) and feedback-based learning (Peñaloza et al., 2016). Koul and Lloyd (1998) examined learning ability for familiar word-novel symbol (i.e., blissymbol) pairings in PWA using a picture matching task that required pointing the symbol that corresponded with a spoken word. They found that PWA showed comparable performance to that of a healthy control group and superior to a right hemisphere lesion group on receptive learning and recognition at 1 week. The degree to which a word-referent association can be guessed when a symbol and its label appear together modulated learning ability in all three groups, while visual complexity failed to do so. Breitenstein et al. (2004) examined incidental probabilistic learning involving higher statistical co-occurrence of correct versus incorrect pseudoword-known object picture pairings during learning separately in young controls and two people with Broca's and Wernicke's aphasia, respectively. Although the task presented a single pseudoword-picture pair per learning instance, referential ambiguity was present across learning trials as pseudowords and their corresponding pictured concepts were not always presented together. Results from the healthy participants indicated successful learning, novel word meaning knowledge and long-term retention of trained words, with steeper learning curves for a subgroup receiving visual feedback after training. Both PWA showed above-chance learning during training and on the transfer test after one training session without feedback, and the patient with Broca's aphasia who received an additional training session 10 months apart showed continued retention of the learned word-picture associations. Similarly, Peñaloza et al. (2016) examined learning ability for pseudoword-referent mappings under referential ambiguity in PWA and healthy controls. In this paradigm, referential ambiguity occurred within learning instances since each trial presented a trained pseudoword with two novel visual referents (target and foil) for participants to choose the correct word-referent mappings followed by feedback on their accuracy (Fig. 4 C). Results showed that PWA were slower and less accurate in learning relative to healthy controls, yet all groups were significantly above chance on an immediate recognition test with only minimally decreased performance on the 1-week follow-up recognition test.

The evidence reviewed here demonstrates that semantic and grammatical properties of words can be acquired incidentally by some PWA although learning is constrained by aphasia type and related language processing deficits (Grossman and Carey, 1987), and that some PWA can learn novel word-referent mappings under referential ambiguity in associative, probabilistic and feedback-based tasks (Breitenstein et al., 2004; Koul and Lloyd, 1998; Peñaloza et al., 2016) even in severe aphasia (Koul and Lloyd, 1998). While these studies suggest that feedback may accelerate initial word learning in healthy adults (Breitenstein et al., 2004) and benefit learning and long-term maintenance in some PWA (Peñaloza et al., 2016), feedback may not be necessary to ensure successful learning and maintenance in some cases (Breitenstein et al., 2004).

Research in the non-linguistic domain has shown impaired probabilistic learning in PWA with diverse aphasic profiles (Vallila-Rohter and Kiran, 2013) possibly related to feedback processing difficulties and ineffective learning strategies (Vallila-Rohter and Kiran, 2015). Overall, this contrasting evidence suggests that more research is needed to evaluate incidental learning in aphasia across the verbal and non-verbal domains. Feedback effects on word learning in PWA require more detailed studies that directly contrast learning with and without feedback across comparable conditions. Finally, the extent to which different levels of conscious processing in incidental learning (Kelly, 2012) modulate differences in performance in PWA across learning paradigms is an open issue for future research.

#### *4.4.1. Factors that influence incidental language learning*

There is evidence that PWA with relatively preserved lexical-semantic abilities also show better incidental semantic learning (Grossman and Carey, 1987). Also, verbal STM modulates word learning under referential ambiguity in feedback-based tasks, and although lexical-semantic and phonological abilities have been associated with this form of word learning, their effects are confounded by aphasia severity (Peñaloza et al., 2016). Aphasia severity has been shown to hinder both learning rate and accuracy in word learning under referential ambiguity although more severely affected PWA may show improvements over time with additional exposure (Peñaloza et al., 2016) providing evidence of learning even in severe cases (Koul and Lloyd, 1998). Findings also suggest clinical aphasic profile/ lesion location plays a role in learning, with a double dissociation between lexical-semantic incidental learning (impaired in Wernicke's but not in Broca's aphasia) and syntactic learning (impaired in Broca's aphasia but not in Wernicke's aphasia) (Grossman and Carey, 1987). These findings align with evidence of impaired word learning under referential ambiguity associated with inferior frontal damage relative to non-frontal lesions (Peñaloza et al., 2016) (Fig. 4D), although probabilistic learning of novel word-known referent mappings has been demonstrated in PWA with agrammatism (Breitenstein et al., 2004). Finally, as with implicit learning, deficits in verbal STM and inferior frontal lesions coexist in PWA. Incidental word learning under referential ambiguity is impaired in PWA with anterior lesions, although better verbal STM and learning ability have been found in PWA with posterior lesions (Peñaloza et al., 2016). Moreover, lesion effects on word learning are significantly reduced when additionally controlling for the effects of verbal STM in aphasia (Peñaloza et al., 2016), making it difficult to disentangle independent contributions for verbal STM and frontal damage. In summary, while similar factors seem to influence both incidental and implicit language learning in aphasia, this interpretation requires caution since evidence from incidental language learning research is limited to a small number of experimental tasks that are available to date.

### *4.5. Important remarks about implicit and incidental learning in aphasia*

Studies of implicit and incidental learning in aphasia (Sections 4.3 and 4.4) differ in notable ways in terms of the specific learning mechanisms addressed across experimental tasks, and reflect varying levels of task difficulty, type of stimuli and sensory modality. Although these studies have been classified as mainly tapping implicit and incidental learning processes according to generally accepted definitions, these learning paradigms do not preclude the recruitment of explicit learning processes and MTL structures (Robertson, 2007; Rodríguez-Fornells et al., 2009; Smith et al., 2014). Evidence for this possibility is provided by Goshke et al. (2001) who reported one participant with Broca's aphasia being able to verbally reproduce a full phoneme sequence on an offline test despite showing no evidence of online phoneme sequence learning. Of note, PWA with agrammatism can present overall spared sequential learning under implicit but not under explicit conditions, possibly due to increased difficulty in using overt learning strategies (Schuchard and Thompson, 2014) or interference from explicit information increasing WM requirements (Boyd and Winstein, 2006). This evidence suggests that implicit/incidental and explicit mechanisms do not always play an exclusive role in learning and may place different cognitive demands. There is thus reason for exerting caution when interpreting the findings reviewed here, and these issues should be tackled with improved methodologies in future research.

### *4.6. Language learning and treatment response in aphasia*

#### *4.6.1. The relationship between learning ability and treatment gains*

Only a few studies have examined both word learning and response to language therapy in aphasia (see Table 4 for a description of these studies and their most relevant findings). The single case study reported by Tuomiranta et al. (2014b) demonstrated that effective word learning ability is closely mirrored in successful vocabulary re-learning, both being supported by spared processing abilities (i.e., spared orthography versus impaired phonology) and their associated brain regions (Fig. 3). The reported patient showed remarkable new word learning ability with perfect verbal recall comparable to healthy controls and learning maintenance for 6 months, and vocabulary re-learning for all trained words with maintenance of gains for 9 weeks. These findings support both the association between word learning ability and response to anomia therapy and past research showing that learning methods that best promote expressive language learning in healthy speakers can lead to successful treatment outcomes in PWA (Basso et al., 2001).

Another case series study by Laganaro et al. (2006) demonstrated that three PWA receiving computerized anomia therapy based on written naming and feedback showed satisfactory improvement in treated items, with two PWA showing generalization to untrained items and maintenance of gains for one month. All three PWA also demonstrated new word learning ability for at least half of the trained abstract drawing-pseudoword pairs, despite performing below healthy controls. Importantly, phonological neighborhood influenced both treatment gains in one patient and new word learning in all healthy controls and another PWA, suggesting that similar facilitation processes may underlie treatment and learning gains by establishing new connections or restoring premorbid ones for novel and existing lexical representations via shared sub-lexical units. More recently, Dignam et al. (2016) conducted the only large group study to examine this association in thirty PWA who received therapy consisting of semantic feature analysis, phonological component analysis, and computerized therapy focused on repetition, picture naming and cueing in either a 3-week intensive or an 8-week distributed schedule. Both groups achieved significant therapy gains in naming for treated and untreated items which were maintained at 1 month. Participants also showed significant improvement on a novel word learning task with better receptive recognition relative to expressive recall. This study also found a significant association between immediate therapy gains on treated items and receptive word learning, although this association was non-significant at 1 month. As commented earlier, PWA with predominantly lexical-semantic deficits showed impaired word learning, revealing a modulatory effect of the locus of language breakdown. Both learning ability and treatment gains were

**Table 4**
Studies of language learning and language treatment in aphasia.

| Study | Participants | Stimuli | Learning task/ duration | Learning measures | Main findings | Factors influencing learning |
|---|---|---|---|---|---|---|
| Tuomiranta et al. (2014b) | 1 PWA (AA)<br>5 HC (exp. 1) | *Exp. 1:* 20 novel unfamiliar word-picture pairings (tools[a]).<br>*Exp. 2:* 20 new pseudoword-picture pairings (tools[a]).<br>*Exp. 3:* 42 known word-familiar object pairs and 21 untrained control pairs. | *Design exp. 1:* associative learning (auditory + orthographic modality).<br>*Duration:* 4 training sessions/ 5 follow-up test sessions up to 6 months.<br>*Design exp. 2:* associative learning (auditory versus orthographic modality).<br>*Duration:* 2 sessions.<br>*Design exp. 3:* word re-learning (treatment) via orthography.<br>*Duration:* 18 treatment sessions/ 5 follow-up test sessions up to 9 weeks. | -*Exp.1:* naming tests at 1 day, 1, 4, 8 weeks, and 6 months post-training.<br>-*Exp. 2:* naming tests during learning.<br>-*Exp. 3:* naming tests and sentence production 1 and 2 days, and 1, 4 and 9 weeks post-training. | -*Exp. 1:* AA learning gains and maintenance on par with HC, showing full acquisition in naming tests and maintenance for 6 months post-training.<br>-*Exp. 2:* spared learning in the orthographic modality but impaired learning in the auditory modality.<br>-*Exp. 3:* perfect naming accuracy and sentence production, high maintenance on both measures at 9 weeks testing. | -Spared reading for words and pseudowords (orthography) but severe repetition impairment for words and pseudowords (phonology).<br>-Damage to the arcuate fasciculus.<br>-Increased activation in spared left occipital and frontal regions and right hemisphere during reading (FMRI).<br>-Increased activation (bilateral hippocampal and right hemisphere temporo-frontal) during word learning (FMRI). |
| Laganaro et al. (2006) | 3 PWA (AH, TM, and PG).<br>8 HC (exp. 2) | *Language therapy:* 100 words (2 sets of 50 treated items) and 290 untreated control items.<br>*Word learning*: 20 novel word-abstract picture pairings. | *Language therapy:* computer-assisted anomia therapy for 2 subsequent word sets via writing (keyboard).<br>*Duration:* 2 therapy periods for each PWA (AH = 3 sessions, TM = 5 sessions, PG = 6 sessions).<br>*Word learning:* associative learning via writing (keyboard).<br>*Duration:* 3 sessions, 1 test session 1 month post-study (PG, TM). | *Language therapy:*<br>-Accuracy for written naming responses during therapy.<br>-Naming test after first treatment period (100 items), second therapy period (390 treated and untreated items), and 1 month after treatment.<br>*Word learning:*<br>- Accuracy for written naming responses during learning. | *Language therapy:*<br>-All PWA increased naming for treated items, only TM improved on untreated items.<br>-AH and TM also improved on the second set.<br>-PG showed slower recovery to reach similar naming levels.<br>-PG and TM maintained treatment gains for 1 month.<br>*Word learning:*<br>-PWA learned at least half of the trained items, although well below the HC. | *Language therapy:*<br>-Improvement predicted by phon. neighborhood and image agreement for PG, and by words age of acquisition for AH and TM.<br>*Word learning:*<br>-Learning predicted by phon. neighborhood in AH and the HC. |
| Dignam et al. (2016) | 30 PWA: 28 completed therapy across two groups (intensive or distributed therapy) and 30 completed the word learning task. | *Language therapy:* 24 words and 24 untreated control items.<br>*Word learning:* 15 novel word-picture pairings (tools[a]). | *Language therapy:* Semantic feature analysis, phon. components analysis, and computer therapy (repetition, picture naming and cueing) for word retrieval deficits.<br>*Duration:* 14 h per type of therapy over 3 or 8 weeks (intensive vs distributed therapy).<br>*Word learning:* explicit associative learning of novel word-picture pairings.<br>*Duration:* 3 sessions. | *Language therapy:*<br>-Naming tests (treated and untreated items) immediately and 1 month after therapy.<br>*Word learning:*<br>-3 recall (naming) and recognition tests after each training session. | *Language therapy:*<br>-23 PWA showed significant improvements on naming for treated items after therapy, 19 maintained gains 1 month after.<br>-8 PWA showed treatment gains for untreated items after therapy, 6 PWA maintained gains 1 month after.<br>*Word learning:*<br>-PWA showed large variability in learning ability.<br>-4 PWA showed significant expressive learning and 19 showed receptive learning (recognition) after training.<br>-Receptive learning was correlated with language outcomes after therapy but not at 1 month post-therapy. | -Therapy gains (treated items) and receptive word learning were correlated with aphasia severity and lexical-sem. processing after therapy and 1 month after.<br>-Word learning was not correlated with non-word repetition or digit span.<br>-Word learning was influenced by locus of language breakdown: 7 out of 9 PWA with semantic deficits failed to learn novel words, but all PWA with phonological deficits showed significant word learning. |

PWA = people with aphasia; HC = healthy controls; Exp. = experiment; Phon. = phonological; Lex-sem. = lexical-semantic.

[a] Tools from the “Ancient Farming Equipment” (AFE) paradigm (Laine and Salmelin, 2010).

modulated by aphasia severity and lexical-semantic processing abilities.

### 4.6.2. *Conclusions about learning ability and treatment response in aphasia*

The evidence reviewed here on the association between word learning ability on language treatment response immediately after therapy (Dignam et al., 2016; Tuomiranta et al., 2014b) indicates word learning as a potential mechanism supporting direct treatment effects on word retrieval deficits in aphasia. It is worth noting the substantial inter-individual variability in both learning ability and response to language therapy in aphasia (Best and Nickels, 2000; Dignam et al., 2016; Laganaro et al., 2006). Indeed, the association between preserved learning and positive treatment response is observed in some, but not all PWA, as some individuals with successful learning may present unsuccessful treatment outcomes (Dignam et al., 2016). Several factors may influence this variation in the association between word learning and therapy response. For instance, PWA may demonstrate learning when the specific learning process under examination engages or relies predominantly on spared language processing abilities (Dignam et al., 2016; Kroenke et al., 2013; Tuomiranta et al., 2011, 2012) and verbal STM for specific language representations (Freedman and Martin, 2001), either phonological or lexical-semantic in nature. Indeed, PWA with phonological processing impairment also show poor learning and vocabulary re-learning via phonology (Tuomiranta et al., 2014b) although they can achieve both successful word learning and treatment outcomes via spared lexical-semantic processing (Dignam et al., 2016) and preserved orthography (Tuomiranta et al., 2014b). Similarly, the effects of phonological neighborhood associated with both novel word learning and treatment gains (Laganaro et al., 2006) suggest that some PWA may benefit from analogous psycholinguistic characteristics defining training and treatment sets and knowledge of phonological structure. In addition, aphasia severity may influence both learning ability and language treatment response (Dignam et al., 2016), placing constraints on the availability of language and cognitive abilities necessary to enable change and improvement. Moreover, better integrity of white matter tracts supports better word learning ability (Coran et al., 2020) and spared brain regions may provide an alternative route for new word learning and vocabulary re-learning when critical regions supporting other language processing abilities are damaged (Tuomiranta et al., 2014b). Therefore, individual differences in language treatment response and language learning success may at least partially reflect variation in the availability of spared language and cognitive abilities supporting learning, and the integrity of their underlying neural substrates in PWA. An alternative yet complementary hypothetical explanation for differences in the association between learning and treatment response at the individual level, is that different mechanisms other than learning may underlie treatment-induced recovery for some individuals (Dignam et al., 2016; Martin et al., 2006). This deserves further examination.

It is important to bear in mind that language learning is not a unitary process, as it is supported by different memory systems, relies on different cognitive processes and may engage different brain regions depending on specific task demands. Therefore, it is reasonable that the relationship between learning performance and treatment response shows different degrees of strength across studies since specific treatment approaches and learning tasks may tap different learning mechanisms (Wang et al., 2020). Further, PWA may show intra-individual variation across learning measures, with learning outcomes depending on the learning approach employed. Thus, not all learning measures may equally predict treatment response across and within individuals, in the same way that different language interventions may be useful for only some but not all patient profiles (Basso et al., 2001). Finally, different metrics of treatment effects are commonly employed in treatment studies, and these metrics may also differ in their association with specific aspects of learning (Wang et al., 2020).

As studies examining language learning and language therapy in aphasia have employed explicit associative word learning paradigms, it remains unknown whether there is an association between implicit language learning and implicit treatment benefits in aphasia. One study examining nonverbal implicit learning and implicit language therapy for sentence comprehension in agrammatic aphasia reported significant learning in a visual SRTT task for most participants although overall language treatment effects were non-significant, making it difficult to assess this association (Schuchard et al., 2017b). It is possible that other implicit learning mechanisms are more closely related to implicit treatment (e.g., AGL and syntactic processing, Schuchard and Thompson, 2014; Cope et al., 2017) or that linguistic as opposed to non-linguistic learning is more closely related to language treatment effects (but see Hoen et al., 2003 for improvements of sentence comprehension in agrammatism following explicit training of nonverbal sequences). Whether preserved implicit learning promotes successful language treatment outcomes remains an important open question for future research.

## 5. Incorporating memory and learning principles in language rehabilitation

This review focused on characterizing language learning ability (entailing the acquisition of partially or fully novel linguistic information) in aphasia as a construct measured independently from language therapy to evaluate its functionality and its possible contributions to language rehabilitation. Thus, reviewing studies that incorporate memory and learning principles in the treatment of pre-existing vocabulary without measuring verbal learning separately was beyond the scope of this work. Nonetheless, it is worth noting that research focused on principles of explicit memory such as retrieval practice and implicit memory such as priming remains important in improving our understanding on relevant memory-based mechanisms that could facilitate re-accessing preexisting lexical knowledge in aphasia. For instance, studies focused on the implementation of distributed practice in naming therapy suggest that memory retrieval factors known to enhance the acquisition of novel linguistic knowledge can also facilitate access to existing word representations that become inconsistently available in aphasia (see Middleton et al., 2020 for a review). With regard to priming, recent research has demonstrated typical semantic and repetition priming effects in PWA although the efficiency of linguistic information processing may decay with increasing processing complexity (Silkes et al., 2020). Moreover, contextual priming (i.e., massive repetition priming of target words while manipulating their relationships to other semantically or phonologically related items) can have differential effects on PWA and facilitation effects on lexical retrieval may depend on whether the source of impairment is semantic or phonological (Martin and Laine, 2000). Further, there is evidence that structural priming can be an effective treatment paradigm to facilitate syntactic production (Lee and Man, 2017), and lexical retrieval (see (Lindsey et al., 2020) for a review). This evidence indicates that priming could be a potential mechanism to strengthen automatic spreading activation and facilitate language improvement in aphasia. Similarly, and taking a novel approach, more recent research has examined explicit associative learning practice with unfamiliar items as a means to stimulate language-related functions in aphasia (Coran et al., 2020). This study demonstrated that after novel word learning practice, PWA can show significant improvements in verbal STM and some degree of improvement on language and verbal learning measures. Critically, this change in language-related functions was rather specific, since no significant change was observed on language-unrelated control tasks. Altogether, this literature suggests that examining how principles of memory and learning can be incorporated in language therapy seems fundamental to ultimately translate both memory/learning theory and basic cognitive psychology evidence into clinical practice.

## 6. Verbal learning in aphasia as it relates to theories of language learning in the healthy brain

It is worth considering how verbal learning ability in PWA relates to the theoretical models that account for the role of memory and learning systems in language learning reviewed in Section 3. Most studies have shown that some PWA can demonstrate explicit associative word learning, which entails binding processes between words and conceptual representations known to rely on the hippocampus and other MTL structures as proposed by the DP (Ullman, 2001, 2004), the CLS (Davis and Gaskell, 2009; McClelland et al., 1995) and the INM (Rodríguez-Fornells et al., 2009) models. The recruitment of the declarative memory system has been corroborated via fMRI evidence of increased bilateral hippocampal activation during successful new word learning in aphasia (Tuomiranta et al., 2014b). Structural neuroimaging studies have also confirmed the contribution of white matter tracts to word learning in PWA in agreement with the INM framework (Rodríguez-Fornells et al., 2009). The integrity of the left arcuate fasciculus as part of the dorsal audio-motor interface of the INM model seems essential for phonological processing and learning such that PWA with better preservation of this dorsal tract show better ability to learn novel words (Coran et al., 2020) while PWA with damage in this tract present with impaired auditory word learning based on phonology (Tuomiranta et al., 2014b). Also, the white matter tracts involved in the ventral meaning interface of the model contribute to the acquisition of novel semantic information (Ripollés et al., 2017) and severe damage to these tracts can preclude word learning in aphasia (Coran et al., 2020). The INM model further proposes that the white matter connecting MTL structures as part of the episodic-lexical interface should also be essential to support the acquisition of novel linguistic information. There is evidence that the declarative memory system supports vocabulary learning in aphasia (Tuomiranta et al., 2014b), and the integrity of MTL regions including the hippocampus and the surrounding white matter modulates language training-induced recovery in aphasia (Meinzer et al., 2010). Thus, these findings suggest that damage to white matter tracts connecting critical regions within and across the language processing and memory/learning systems in the left hemisphere may impact both language learning success and treatment response and recovery in aphasia.

Notably, the association between frontal lesions and impaired incidental language learning (Grossman and Carey, 1987; Peñaloza et al., 2016) aligns well with the DP model (Ullman, 2001, 2004). However, the evidence from implicit learning is only partially consistent with this model's predictions. As expected, sequential learning (Dominey et al., 2003; Goschke et al., 2001), SL (Peñaloza et al., 2015) and AGL (Cope et al., 2017; Dominey et al., 2003) is impaired in individuals described as presenting Broca's aphasia, agrammatism or non-fluent aphasia with damage to anterior frontal regions and/or the basal ganglia. Yet, deficits are not consistent across modalities or task requirements (Cope et al., 2017; Dominey et al., 2003; Goschke et al., 2001), and spared sequential learning and AGL has been reported in agrammatic aphasia (Schuchard and Thompson, 2014; 2017a). This intra- and inter-individual variability in learning performance suggest that different neural mechanisms may underlie different forms of implicit learning. Thus, a detailed characterization of both neural damage localization and performance across different implicit learning tasks in PWA would help in clarifying the contribution of specific brain regions to different forms of implicit language learning.

Finally, the evidence that verbal STM/WM modulates learning ability in PWA (Bormann et al., 2020; Kroenke et al., 2013; Peñaloza et al., 2015) supports theories that highlight its contribution as a gateway to word learning (Baddeley et al., 2003; Gupta et al., 2003). Studies also confirm that STM/WM is not a unitary construct, since phonological and semantic STM can make independent contributions to the acquisition of phonological and semantic information in aphasia (Freedman and Martin, 2001) and the presence of impaired word learning following left IFG lesions (Peñaloza et al., 2015, 2016) supports the contribution of this region to verbal STM/WM (Martin et al., 2021).

## 7. A potential explanatory account of impaired versus spared language learning and its relationship to language therapy outcomes in aphasia

This review provides important insights about the interaction between language processing and memory/learning systems in aphasia. It also underscores the importance of considering them as neurally differentiated systems with reciprocal communication and both shared structures and cognitive processes (Roger et al., 2022) that enable different aspects of language learning. Based on the findings reviewed here, we propose a potential explanatory account for language learning capacity in PWA considering relevant theoretical models of memory and learning. As described in Section 3, associative explicit language learning requires functional reciprocal connections between MTL regions which contribute to encoding and binding processes and neocortical regions (left fronto-temporal language processing areas, Gore et al., 2021) where newly acquired linguistic information is transferred for consolidation and long-term storage (Davis and Gaskell, 2009). STM/WM mechanisms further contribute to the initial maintenance of novel language input (Gupta and Tisdale, 2009) with different brain regions supporting the maintenance of phonological (SMG, supplementary motor and posterior IFG regions) and semantic (opercular IFG, AG, and pSTS) information (Martin et al., 2021). In addition, white matter tracts connecting MTL and neocortical regions as well as dorsal and ventral white matter pathways connecting regions crucial for phonological and conceptual-semantic processing also contribute to this language learning process (Rodríguez-Fornells et al., 2009). Similar critical interactions are assumed for the frontal, basal ganglia, parietal and cerebellar regions involved in implicit language learning (Ullman, 2001, 2004).

Although damage to MTL structures is unlikely after a typical brain insult leading to aphasia, the integrity of different brain regions relevant for the final consolidation of newly acquired vocabulary in the language processing system, verbal STM and implicit language learning is often compromised. Thus, damage to these areas and their white matter connections may hinder language learning success in PWA via the following potential mechanisms. First, memory and learning processes for language partially rely on linguistic skills and their neural bases to enable the processing of novel incoming phonological and conceptual language codes (Grossman and Carey, 1987) for initial encoding. Learning can also build upon existing phonological and lexical-semantic information (Laganaro et al., 2006; Marshall et al., 1992) which becomes impaired or difficult to access in aphasia (Laine and Martin, 2006). Therefore, damage to language-related neural regions may ultimately place input and output processing constraints for language learning, impairing the initial acquisition and/ or the verbal demonstration of recently acquired linguistic information (Ween et al., 1996). This is likely reflected in the variation observed in the receptive versus expressive learning performance in aphasia (e.g., Dignam et al., 2016). Second, verbal STM/WM is essential for language learning in the initial retention and maintenance of novel input (Gupta and Tisdale, 2009) for the creation of language memory traces that can be later consolidated in the long-term (Davis and Gaskell, 2009). Hence, damage to regions critical for verbal STM/WM may lead to faster rates of decay of novel linguistic information and hinder its capacity to support the initial formation of new language representations. Finally, as asserted by the CLS model (Davis and Gaskell, 2009; McClelland et al., 1995), consolidation processes mediate between hippocampus-dependent rapid learning and neocortex-dependent slow learning systems to achieve the stabilization of lexical representations. However, if neocortical regions supporting the long-term consolidation of newly acquired linguistic information are damaged, it is likely that such information has more difficulty in becoming hippocampus-independent and evolving into stable representations in the language processing system as suggested by recent critical research (Gore et al., 2021). This is supported by findings from Gore et al. (2021) who found that after learning, greater activation of the left hippocampus in older healthy adults is associated with lower accuracy, longer RTs and better long-term maintenance when naming newly acquired words, whereas greater activation in neocortical regions that support already established vocabulary (i.e.: left IFG and anterior temporal lobe) is associated with higher accuracy and shorter RTs.

Importantly, and under the light of these findings, the relationship between explicit associative word learning and treatment gains in PWA immediately post therapy but not 1 month after (Dignam et al., 2016) suggests that learning mechanisms may mainly support the initial process of strengthening memory traces for words that become difficult to access after brain insult in which reliance on the hippocampus and MTL structures is critical for successful acquisition (Davis and Gaskell, 2009; McClelland et al., 1995). However, if neocortical integrity following brain insult is not sufficient to ensure more effective reliance on the language system to sustain long-term consolidation processes promoted via treatment, it is likely that PWA show less stabilization and worse decay without further training. This is in line with evidence of higher hippocampal reliance after new word learning being associated with worse long-term maintenance in healthy older adults (Gore et al., 2021).

In sum, this tentative account suggests that brain damage may impair input processing and short-term maintenance for initial encoding and disrupt output processes and long-term storage and consolidation of new linguistic knowledge despite general preservation of memory and learning structures. On this account, the functionality of individual language learning ability in PWA would ultimately depend on (i) the degree of integrity of critical regions in the language and memory/learning systems and their connections to sustain the learning process across different stages (Coran et al., 2020; Peñaloza et al., 2015, 2016) and (ii) the availability of alternative cognitive and neural resources for learning to compensate for damage in critical brain regions (Tuomiranta et al., 2014b). This view is in line with similar proposals (Gore et al., 2021) that further suggest that language therapy success may depend on the amount of damage to brain regions critical to learning in the CLS framework and the extent to which treatment can promote language re-learning and its long-term stabilization.

## 8. Concluding remarks and clinical considerations

Most accounts of aphasia therapy have not considered theories of learning and memory systems in understanding the mechanisms supporting language treatment outcomes in PWA. Notably, the last decades have revealed a growing research interest in language learning abilities in aphasia and their relationship with language rehabilitation. The studies reviewed here have provided important evidence for the initial characterization of language learning abilities in aphasia, demonstrating slower learning rates and overall less successful learning performance as compared to healthy speakers across different explicit and implicit learning paradigms. As with language therapy response, there is a large individual variability in language learning ability in PWA reflecting the influence of (i) *patient-related factors* (i.e., individual differences in learning ability, individual profile of preserved versus impaired language processing abilities and verbal STM, and availability of alternative spared language and cognitive processes to support learning), (ii) *aphasia-related factors* (i.e., aphasia type, severity and locus of language breakdown), and (iii) *neurological factors* (i.e., lesion location and the integrity of critical neural resources to support learning). While still limited, evidence on the relationship between verbal learning and language treatment in aphasia underscores two preliminary yet converging findings. First, there is an association between immediate anomia treatment gains and explicit associative novel word learning ability via repetition (Dignam et al., 2016), which suggests this form of verbal learning may have independent prognostic value for treatment response in PWA. Second, explicit associative novel word learning via orthography is also effective to achieve successful lexical acquisition in PWA with phonological processing deficits (Tuomiranta et al., 2014a, 2014b) and can be used to effectively re-learn premorbid vocabulary (Tuomiranta et al., 2014b). These findings suggest that (i) explicit associative word learning mechanisms could support treatment-induced recovery in aphasia, and (ii) training methods addressing explicit associative learning via the auditory and orthographic modalities may be candidate procedures to be incorporated into future treatment studies to evaluate their contribution to language recovery.

Critically, this review underscores the cognitive neuropsychology approach which highlights the relevance of a detailed case-by-case examination of language learning ability in PWA to inform both basic cognitive neuroscience and clinical rehabilitation research. Studies involving cases with varying degrees and forms of impaired learning performance can provide important insights about the functional interplay between language and memory/learning systems, and the neural substrates that are essential to support language learning in the healthy brain. For example, evidence of damage to left inferior frontal regions (Peñaloza et al., 2015, 2016) and the basal ganglia (Cope et al., 2017) being associated with impaired language learning in aphasia suggests an essential role for these regions in different forms of language learning, which is consistent with current theoretical models (Ullman, 2001, 2004). On the other hand, cases of spared learning performance can reveal abilities and neural regions that enable language learning despite brain damage. These cases indicate possible alternative routes to achieve successful learning and point to effective methods to promote learning processes in other individuals with similar characteristics. In this vein, case studies have revealed successful learning via orthography despite impaired phonology associated with the recruitment of hippocampal and fronto-temporal regions in the unaffected right hemisphere (Tuomiranta et al., 2014b), as well as higher word learning performance in the presence of better integrity of dorsal and ventral language pathways (Coran et al., 2020). This pinpoints important preserved structures and spared abilities that can support language learning in aphasia.

Although preliminary, the evidence reviewed in this article has important clinical implications. It indicates word learning potential in some aphasic patients despite the presence of language impairment and suggests a role of learning processes in aphasia therapy outcomes. Individual learning profiles characterized in terms of receptive and expressive explicit associative learning across different modalities could be employed as a diagnostic-prognostic tool in baseline neuropsychological assessments to identify individual patterns of impaired abilities critical to target during treatment and unveil preserved learning abilities to build upon in rehabilitative interventions. For instance, single-session clinically-feasible word learning tests involving receptive and expressive measures (Navarrete et al., 2022) that evaluate learning ability across the auditory versus the orthographic modalities could inform on individual potential for vocabulary re-learning and improvement on single word production, and could signal the processing channels that may be available to effectively support vocabulary re-learning interventions for PWA. This information could help select methods that promote effective learning and could be further augmented when combined with advanced structural and functional neuroimaging to guide successful rehabilitation.

## 9. Limitations and future directions

The studies included in this review are largely heterogeneous in their methodological approach to language learning in aphasia. They show important differences regarding learning paradigms, training stimuli, task difficulty, measures of learning and criteria employed to define successful and impaired learning. Thus, comparisons across study findings are limited by this variability. Further, most evidence on language learning in aphasia comes from studies with small heterogeneous patient samples and single case studies which may limit the statistical power to detect effects of interest. Replication with larger samples with different loci of breakdown, degree of aphasia severity, and language and cognitive profiles is needed to clarify divergent findings and to confirm preliminary results from studies using unique methodological approaches. Also, only a few studies have reported individual lesion location data, and most of them have employed broad descriptions of lesion distribution as reported by clinical MRI reports. More research based on structural and functional neuroimaging methods is required to better elucidate the brain-behavior relationships concerning learning ability in aphasia. Similarly, more evidence is needed to establish if different forms of implicit/incidental language learning are relevant to aphasia rehabilitation and how they could inform individual treatment plans in the future.

So far, the leading questions for research in language learning in aphasia have been whether PWA can demonstrate learning, how language learning varies across individuals according to their language, cognitive, and lesion profiles, and whether language learning is associated with language treatment. This review provides an overview and critical discussion of the existing evidence that addresses these questions. However, the following questions remain open for future research and may motivate significant advances in the field:

- What are the methods that best promote language learning in PWA and are there any modifiable factors that may help to boost their learning performance?
- How do language learning abilities differ within individuals according to their language, cognitive, and lesion profiles?
- Are all language learning measures equally predictive of language treatment response and how is this association consistent across different types of therapy?
- Which factors drive this association and how can language rehabilitation best capitalize on principles of memory and learning systems to improve treatment response?
- How can learning profiles and advanced neuroimaging information be best combined to inform potential success of rehabilitation programs?

Research in language learning with healthy individuals may provide important insights and methodological approaches to address different factors that could promote language learning in PWA. Some of these factors worth studying in aphasia include motivational aspects associated with the reward system involved in language learning (Ripollés et al., 2014), the benefits conferred to new word learning by physical exercise (McSween et al., 2020), sleep consolidation processes (Dumay and Gaskell, 2007) and non-invasive cortical stimulation interventions (Perceval et al., 2020).

It is important to bear in mind that intra-individual variability in language learning is expected even in healthy individuals across learning tasks. This reflects differential recruitment of cognitive abilities (Gupta et al., 2009), including memory/learning systems and their underlying brain regions (Ullman, 2001, 2004), and also depends on the particular aspect of language learning undergoing examination. Individual learning performance can also differ over the lifespan reflecting aging-related changes in cognitive and neural resources required for successful learning (Dennis and Cabeza, 2011; Ward et al., 2020). Therefore, the examination of intra-individual variability across different learning tasks, training stimuli and sensory modalities in PWA is of great importance to characterize preserved versus impaired learning abilities at the individual level in relation to language, cognitive, and lesion profile to optimize individual rehabilitation plans. Complementary group-level analyses could further help identifying the most sensitive measures of language learning ability that best predict treatment response across different types of interventions.

Common factors that support both language learning and language recovery are also worth of study in aphasia. For instance, neuroimaging studies could help to determine the extent to which the same brain networks are recruited during novel word learning and pre-existing vocabulary re-learning via treatment and to identify the key regions that contribute to both processes. Also, recent research has shown that noninvasive repetitive stimulation of the cingulo-opercular multiple demand cortex can enhance new word learning (both learning rate and accuracy) in healthy speakers (Sliwinska et al., 2017) and activation in this region predicts language recovery in aphasia (Geranmayeh et al., 2017). This suggests that domain-general neural systems such as the cingulo-opercular brain network involved in different cognitive processes including cognitive control (Brownsett et al., 2014) are worth studying in the context of language rehabilitation. In the same line, more research is required to determine whether novel approaches such as intensive novel word learning practice (Coran et al., 2020) can strengthen language and cognitive systems that may support language therapy outcomes in PWA.

Overall, the study of these and other aspects of language learning in aphasia represent promising avenues for research to improve our understanding of the interaction of language and memory/ learning systems in aphasia and its implications to aphasia treatment. We believe that this research will have important implications for the development of theoretical accounts of learning-dependent brain plasticity in aphasia and clinical applications in language rehabilitation.

## Declaration of Competing Interest

None of the authors has competing interests to declare.

## Data availability

No data was used for the research described in the article.

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