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Research report

Cross-situational word learning in aphasia

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ABSTRACT

Human learners can resolve referential ambiguity and discover the relationships between words and meanings through a cross-situational learning (CSL) strategy. Some people with aphasia (PWA) can learn word-referent pairings under referential uncertainty supported by online feedback. However, it remains unknown whether PWA can learn new words cross-situationally and if such learning ability is supported by statistical learning (SL) mechanisms. The present study examined whether PWA can learn novel word-referent mappings in a CSL task without feedback. We also studied whether CSL is related to SL in PWA and neurologically healthy individuals. We further examined whether aphasia severity, phonological processing and verbal short-term memory (STM) predict CSL in aphasia, and also whether individual differences in verbal STM modulate CSL in healthy older adults. Sixteen people with chronic aphasia underwent a CSL task that involved exposure to a series of individually ambiguous learning trials and a SL task that taps speech segmentation. Their learning ability was compared to 18 older controls and 39 young adults recruited for task validation. CSL in the aphasia group was below the older controls and young adults and took place at a slower rate. Importantly, we found a strong association between SL and CSL performance in all three groups. CSL was modulated by aphasia severity in the aphasia group, and by verbal STM capacity in the older controls. Our findings indicate that some PWA can preserve the ability to learn new word-referent associations cross-situationally. We suggest that both PWA and neurologically intact individuals may rely on SL

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mechanisms to achieve CSL and that verbal STM also influences CSL. These findings contribute to the ongoing debate on the cognitive mechanisms underlying this learning ability.

1. Introduction

Determining the relationships between unknown words and their meanings is an essential aspect of vocabulary acquisition. In natural language learning contexts, learning new word-referent mappings can be challenging due to the multiple possible referents available for a given word in a single learning scenario and the limited cues as to which word-referent associations are conclusive. Nevertheless, while conceptual referents may remain indeterminate in a single learning encounter, this referential ambiguity can be resolved cross-situationally, across various learning instances (Trueswell, Medina, Hafri, & Gleitman, 2013; Yu & Smith, 2007). Previous research has demonstrated that cross-situational learning (CSL) might be a fast avenue into effective word learning for infants (Smith & Yu, 2008), children (Suanda, Mugwanya, & Namy, 2014) and adults (Roembke & McMurray, 2016; Yu & Smith, 2007), suggesting that this learning ability might be available throughout the lifespan. However, little is known about the extent to which this learning capacity can be affected in aphasia following focal brain damage, and the cognitive mechanisms that support this ability.

Theories of language learning and its underlying dynamics are highly relevant to aphasia research as they can inform approaches to aphasia diagnostics and intervention. Moreover, an increased understanding of the methods and cognitive abilities that support learning in neurologically healthy individuals may benefit anomia therapy (Basso et al., 2001). There is strong evidence that associative learning methods can aid some PWA to learn single unambiguous word-referent pairings (Kelly & Armstrong, 2009; Tuomiranta, Càmara, et al., 2014; Tuomiranta, Rautakoski, Rinne, Martin, & Laine, 2012). Furthermore, this new word learning ability predicts anomia treatment outcomes (Dignam et al., 2016; Tuomiranta, Càmara, et al., 2014), which supports the idea that anomia therapy may involve new word learning processes (Kelly & Armstrong, 2009).

Only recently, the study of residual new word learning ability in aphasia has been extended into more challenging learning settings involving referential ambiguity. Peñaloza et al. (2016) examined whether fourteen PWA could learn six novel words presented together with a limited set of different possible visual referents. In each trial, a word co-occurred with the target referent and a foil referent of the learning set. The task for participants was to identify the correct word-object associations on the basis of trial-to-trial online feedback. This study found that some PWA demonstrated a preserved ability to learn new word-referent associations from individually ambiguous scenes across several instances, and retain the acquired mappings for up to one week without further training. Although the learning setting employed in that study differed from traditional paradigms measuring CSL without performance-based feedback, these preliminary findings suggest that this learning ability could remain spared in some PWA.

The main aim of the present study was to examine the ability of PWA to learn a small set of word-referent associations through CSL as compared to neurologically healthy individuals. Based on the abovementioned findings, we predicted that CSL would remain functional in at least some PWA. In order to examine CSL in aphasia we employed a modified version of the experimental task reported by Yu and Smith (2007). Briefly, the task includes a series of learning trials, each one presenting 2 spoken words together with 2 pictures of the learning set (i.e., lowest level of within-trial ambiguity with 4 possible word-referent associations per trial) followed by a test. This experimental setting sought to determine whether PWA can simultaneously learn word-referent mappings from trials that are individually ambiguous without relying on performance-based feedback. To this aim, the learning performance of the PWA on the first learning block and test was compared to that of a group of neurologically intact older controls and a young adult group recruited for task validation purposes. In addition, although it has been demonstrated that CSL in this 2×2 condition can be achieved rapidly in healthy adults (Yu & Smith, 2007), previous research has shown that aphasia can impact the speed of learning under referential ambiguity in PWA (Peñaloza et al., 2016). Therefore, our experimental task included three additional learning blocks and tests to fully examine how learning unfolded over time.

A second purpose of the present study was to examine further the hypothesis that CSL is related to statistical learning (SL) mechanisms in healthy individuals and in PWA. This hypothesis is based on current statistical-associative learning accounts of CSL which propose that CSL can be achieved via SL mechanisms through the statistical computation of the co-occurrence of words and referents across several learning instances (Smith & Yu, 2008; Yu & Smith, 2007). According to this view, learners could resolve the referential uncertainty problem gradually across learning trials by storing several possible word-referent pairings, accruing and evaluating the statistical evidence of the learning context across multiple undetermined word-referent combinations, and finally mapping individual words to their true meanings (Smith & Yu, 2008; Yu & Smith, 2007). However, other theories of CSL advocate hypothesis-testing accounts such as the “propose but verify” learning strategy (Trueswell et al., 2013). According to this view, learners formulate a single hypothesis as to which is the true referent for a given word from initial exposures, retain this hypothesis, and verify its consistency in subsequent learning trials. The hypothesis is then either confirmed with subsequent supporting evidence or abandoned after contrary evidence, in which case a new hypothesis is formulated for further confirmation or rejection. In contrast to the SL mechanism hypothesis, this alternative account would operate as a fast-mapping rather than a gradual learning process (Trueswell et al., 2013). In addition, more recent studies support hybrid views that can accommodate both accounts of CSL. For instance, memory-based accounts indicate that inferences about word-referent mappings are made on the basis of learning instances encoded in long-term memory (Dautriche & Chemla, 2014), and that memory retrieval mechanisms during CSL can influence the long-term retention of newly acquired word-referent mappings (Vlach & Sandhofer, 2014). As these theories are still developing, the study of the association between CSL and SL is of great relevance because of its potential contribution to the ongoing theoretical debate on the cognitive mechanisms underlying CSL.

Examining whether performance on a traditional CSL paradigm is related to other forms of statistical word learning could provide crucial insights into the contributions of SL mechanisms to cross-situational word-referent mapping. Several studies have reliably shown that SL supports speech segmentation, the ability to detect word boundaries in running speech through the computation of syllable-to-syllable sequential probabilities (Cunillera et al., 2009; Pelucchi, Hay, & Saffran, 2009; Saffran, Aslin, & Newport, 1996; Saffran, Newport, & Aslin, 1996). There is evidence that recently segmented word-like units can be mapped later onto novel referents (Graf Estes, Evans, Alibali, & Saffran, 2007; Mirman, Magnuson, Graf Estes, & Dixon, 2008) and that speech segmentation and single word-referent mapping can occur in parallel (Cunillera, Càmara, Laine, & Rodríguez-Fornells, 2010; Cunillera, Laine, Càmara, & Rodríguez-Fornells, 2010; Thiesen, 2010). Thus, a relationship between speech segmentation and cross-situational word-referent mapping based on the common ground of tracking co-occurrence statistics would further support the idea that SL can help to solve different challenging aspects of learning a new language (Saffran, Aslin, et al., 1996).

It has been demonstrated recently that some PWA can benefit from SL mechanisms in order to segment words from a novel speech stream (Peñaloza et al., 2015), and preliminary evidence with two PWA suggests that probabilistic learning of word-referent mappings can be preserved in aphasia (Breitenstein, Kamping, Jansen, Schomacher, & Knecht, 2004). However, it remains unclear whether new word-referent mapping in aphasia can be achieved cross-situationally through SL mechanisms, and whether word-referent mapping and speech segmentation abilities are related to common SL underpinnings.

Thus, to fill this gap, the present study explored the relationship between CSL and speech segmentation via SL in aphasic and neurologically healthy adults. The participants of the current study were also administered a second task, previously employed with PWA and healthy individuals (Peñaloza et al., 2015), that taps speech segmentation via SL. The task involves exposure to an unknown artificial miniature language where the only reliable cues to word boundaries are the transitional probabilities (TP) between neighboring syllables (i.e., higher TP between syllables forming words, and lower TP between syllables spanning word boundaries). Statistical word learning is then measured through the discrimination of words of the language from foils that were never presented. Based on the hypothesis that CSL is supported by SL mechanisms (Smith & Yu, 2008; Yu & Smith, 2007) we predicted that CSL would be associated with performance on our speech segmentation task tapping SL.

Our third aim was to examine whether the integrity of language and cognitive function after brain damage accounts for variability in word learning ability in PWA. Although word learning may rely on several language and cognitive abilities (Gupta & Tisdale, 2009; Vlach & DeBrock, 2017), previous research indicates that aphasia severity, phonological processing and verbal STM could be related to cross-situational word learning in PWA. Aphasia severity can impact new word learning and vocabulary re-learning (Dignam et al., 2016; Marshall, Freed, & Karow, 2001), and phonological word processing has been associated with phonological word learning ability in aphasia (Gupta, Martin, Abbs, Schwartz, & Lipinski, 2006; Martin & Saffran, 1999). Therefore, we hypothesized that CSL would be modulated by aphasia severity and phonological word processing abilities in PWA.

In addition, word learning also can be influenced by the availability of memory resources and short-term storage and retrieval processes. Past research has demonstrated a strong relationship between verbal STM and vocabulary learning (Gathercole & Baddeley, 1989; Gathercole, Hitch, Service, & Martin, 1997; Gupta, 2003; Service, 1992). Moreover, previous studies with healthy infants and adults have shown that CSL is influenced by memory constraints (Vlach & Johnson, 2013; Vlach & Sandhofer, 2014) and it has been proposed that CSL may rely specifically on STM capacity (Vlach & Sandhofer, 2014) although to the best of our knowledge, this possible relationship has not been previously tested in healthy individuals, let alone PWA. Past research has shown that verbal STM (Martin & Saffran, 1999) and more specifically, phonological and lexical-semantic STM make differential contributions to word learning in aphasia (Freedman & Martin, 2001). The study conducted by Freedman and Martin (2001) found that PWA with phonological STM deficits show impaired ability to learn new word forms and spared ability to learn novel semantic information for known words, while PWA with deficits in lexical-semantic STM show the opposite learning profile. Importantly, in a previous study of word learning under referential ambiguity in aphasia (Peñaloza et al., 2016), we found that aphasia severity, phonological processing and verbal STM (phonological and lexical-semantic STM) were all predictors of word learning, albeit only verbal STM composite scores continued to predict word learning after factoring out the effects of aphasia severity. However, only very few studies of word learning in aphasia have examined the cognitive processes that predict word learning ability and it remains unknown whether verbal STM capacity also modulates CSL ability in PWA.

Accordingly, the present study also aimed to examine the relationships between verbal STM and CSL ability in aphasic and neurologically healthy speakers. More specifically, we studied whether the integrity of verbal STM capacity influences CSL in aphasia, and if individual differences in verbal STM modulate CSL in our healthy older controls. We additionally explored whether phonological and lexical-semantic STM differentially contribute to CSL in both the aphasia and the control group. In line with previous accounts of verbal memory dynamics influencing CSL in healthy adults (Vlach & Sandhofer, 2014) and word learning under referential ambiguity in PWA (Peñaloza et al., 2016), we expected to find a relationship between CSL performance and verbal STM in both the PWA and the healthy older controls.

2. Methods

2.1. Participants

The total sample included 74 right-handed Spanish speaking participants across three groups. The aphasia group consisted of 16 people with stroke-induced chronic aphasia (12 men, 4 women). Their mean age was 57.63 ($SD = 11.45$, $range = 40–78$), their mean number of years of education was 8.63 ($SD = 4.96$, $range = 0–18$), and their average time from stroke onset was 21.44 months ($SD = 10.45$, $range = 6–41$). Nine participants were Spanish monolinguals and 7 were Spanish/Catalan bilinguals. To be included in the study, the participants with aphasia were required to be 30–80 years of age and to have persistent aphasia as determined by formal speech and language assessment at least 6 months after a first single left hemisphere stroke confirmed by CT or MRI scan. Fifteen participants were recruited from the stroke unit of the Hospital Universitari de Bellvitge and one from the Rehabilitation unit of the Hospital de l' Esperança in Barcelona. Table 1 summarizes their demographic and clinical information, as well as their language background according to a brief bilingual language background questionnaire administered together with their language and cognitive assessment.

The healthy control group (hereafter "older controls") included 18 participants (4 men, 14 women). Their average age was 58.67 ($SD = 7.13$, range = 50–77) and their mean number of years of education was 11.39 ($SD = 5.02$, range = 0–17). All of them were Spanish/Catalan bilinguals. The older control group was not significantly different from the aphasic group in terms of age [t (32) = −.314, $p = .76$] or years of education [t (32) = −1.61, $p = .12$].

A third group of 39 undergraduate psychology students at the University of Barcelona (hereafter: "young adults") was recruited to validate the CSL task and to ensure that the standard learning performance was similar to that reported in previous studies (Peñaloza et al., 2015; Yu & Smith, 2007). On average, the young adults (6 men, 33 women) were aged 19.9 years ($SD = 2.62$, $range = 18–29$) and had received 13.97 years of formal education ($SD = 2.32$, $range = 12–20$). All of them were Spanish/Catalan bilinguals except for one Spanish monolingual.

The healthy older and young adults had normal hearing and normal or corrected-to-normal vision as reflected by their responses to short questions that allowed ruling out marked visual and auditory deficits in ordinary life activities. The presence of marked visual or auditory deficits in the participants with aphasia was ruled out based on their medical records and self-reports. They also underwent a basic screening assessment of visual acuity with a traditional Snellen chart employed in their neurological examination at the hospital of recruitment. In addition, they completed the screening version of the Hearing Handicap Inventory for the Elderly (HHIE-S; Ventry & Weinstein, 1982) where all participants were below the cutoff score for audiologic referral. None of the participants had a history of neurological disorders (other than stroke for the aphasia group), severe mental illness, or learning disabilities. All procedures were approved by the ethics committee of the Hospital Universitari de Bellvitge and the University of Barcelona, and all participants gave their written informed consent.

2.2. Language and verbal STM assessment

The presence and type of aphasia were determined with the Spanish version of the Boston Diagnostic Aphasia Examination (BDAE) (Goodglass, Kaplan, & Barresi, 2005). Aphasia severity was determined with the 5-point severity rating scale of this battery. Specific subtests of this battery were used for language background testing as follows. Spontaneous speech was assessed with the conversational and expository speech subtests. Repetition ability was examined using the Sentence repetition subtest. Verbal comprehension was evaluated with the Word comprehension, Commands, and Complex ideational material subtests, as well as with the Token Test (De Renzi & Faglioni, 1978). Naming ability was assessed with the Boston Naming Test (Kaplan, Goodglass, & Weintraub, 2005). Additionally, the semantic and phonemic word fluency tasks (animals and words beginning with the letter "*p*", respectively) were used to assess speeded word retrieval (Cassals-Coll et al., 2013; Peña-Casanova et al., 2009). The performance of the participants with aphasia in these language measures is available in Table 2.

The participants in the aphasia group were also examined with a selection of subtests of the Spanish version of the Temple Assessment of Language and Short-term memory in Aphasia (TALSA; Kalinyak-Fliszar, Kohen, & Martin, 2011; Martin, Kohen, & Kalinyak-Fliszar, 2010). The Phoneme discrimination subtest requires deciding whether two spoken words or nonwords are the same or different. The task in the Rhyming judgments subtest is to decide whether a pair of words or nonwords rhyme. These two tests consist of 20 test trials each. The Nonword repetition test requires repeating 15 nonwords (1, 2 and 3-syllable items). These tests include two interval conditions where the stimuli of each pair are separated by either a 1- or 5-sec delay (Phoneme discrimination and Rhyming judgments), or a response is required 1 or 5 sec after stimuli presentation (Nonword repetition).

Verbal STM was evaluated with four TALSA span tasks that require recalling sequences of words or digits in serial order. The Word repetition span and the Digit repetition span measure the ability to repeat strings of either words or digits in each of 7 string length conditions (1 item, 2 items, etc.). There are 10 strings in each string length condition. The Word pointing span and the Digit pointing span require listening to a sequence of words or digits and pointing to the sequence on a visual array of 9 items. A span size is computed for each subtest using the following formula: string length at which at least 50% of the strings are recalled + (.50 × proportion of

Table 1 – Demographic, language and clinical background of participants with chronic aphasia.

Case	Gender	Age (years)	Education (years)	Language/AoA/Use/Proficiency[a]	TPO (months)	Etiology	Aphasia type	Lesion location
EV	F	64	0[b]	Span/0/100/24	25	I/H	Global	MCA stroke (frontal region)/hemorrhage in lenticular nucleus
CM	M	78	4	Span/0/100/24	25	I	Global	PCA-MCA stroke (fronto-parietal regions + insula + BG)
RG	M	61	18	Span/0/100/24	26	I	Anomic	MCA stroke (frontal regions + insula + BG)
RL	M	51	5	Span/0/100/24	20	I	Fluent	MCA stroke (temporal posterior regions)
DM	M	43	10	Span/0/100/23; Cat/5/0/20[c]	20	I	Fluent	PCA stroke (temporo-parietal regions + subcortical regions)
JM	M	64	8	Span/0/100/24	37	I	Fluent	MCA stroke (posterior frontal regions + insula + BG)
MS	F	40	14	Span/0/75/24; Cat/15/25/20[d]	14	I	Broca	MCA stroke (fronto-parietal regions + insula + caudate nucleus)
JC	M	47	8	Span/0/98/24; Cat/6/2/19[c]	6	I/H	Broca	MCA stroke (fronto-temporo-parietal)/subinsular hemorrhage
ON	M	42	14	Span/0/40/24; Cat/5/60/24[c]	11	I/H	Mixed non-fluent	Extensive MCA stroke (fronto-temporo-parietal regions + BG)/ hemorrhage in lenticular and caudate nucleus
AF	M	69	8	Cat/0/60/23; Span/2/40/22[c]	24	I	Fluent	MCA stroke (parietal perisylvian regions)
JH	M	54	16	Cat/0/10/24; Span/2/90/23[c]	19	I/H	Broca's	Extensive MCA stroke/intracerebral hemorrhage (frontal regions, caudate nucleus)
AH	M	71	3	Span/0/80/16; Cat/40/20/18[d]	8	I	Anomic	MCA stroke (fronto-temporal regions + insula + subcortical regions)
AI	F	57	8	Span/0/100/24	9	I	Non-fluent	MCA stroke (frontal posterior regions + insula)
MR	F	71	6	Span/0/100/21	22	I	Mixed non-fluent	Extensive MCA stroke (fronto-temporo-parietal regions + insula + BG)
GB	M	58	5	Span/0/100/20	36	I	Broca	Extensive MCA stroke (frontal opercular + insular + parietal regions + subcortical regions)
JB	M	52	11	Span/0/100/24	41	I	TCM	MCA stroke (frontal regions + insula + subcortical regions)

TPO = time post-onset; M = male; F = female; I = ischemia; H = hemorrhage; MCA = middle cerebral artery; PCA = posterior cerebral artery; BG = basal ganglia; TCM = transcortical motor.

[a] Bilingual language background questionnaire: Language: Span = Spanish, Cat = Catalan; AoA = age of acquisition (years); Use = self-reported percentage of the time spent speaking each language during the last three years; Proficiency = self-rated score before stroke including speaking, understanding, reading and writing (max. score = 24).

[b] Reading, writing and basic arithmetic skills acquired outside formal education.

[c] Early bilingual.

[d] Late bilingual.

Table 2 – Individual scores of the participants with aphasia in selected BDAE subtests and other language measures.

Language measure	Cases															
	EV	CM	RG	RL	DM	JM	MS	JC	ON	AF	JH	AH	AI	MR	GB	JB
BDAE severity rating	1	1	4	3	5	4	2	3	1	5	3	4	3	2	2	3
BDAE Sent. repetition[a]	**0**	**3**	10	9	9	9	**4**	7	**2**	9	**2**	8	8	9	**4**	9
BDAE Word comp.[a]	**33**	**26**	37	**29**	37	36.5	37	37	**32**	37	35	34.5	**34**	**34.5**	**32**	37
BDAE Commands[a]	**10**	**11**	15	**11**	15	15	14	15	**11**	15	14	**12**	15	13	15	14
BDAE Comp. Id. Mat.[a]	**6**	**8**	12	**4**	10	11	10	10	10	10	**6**	11	**5**	7	**4**	**6**
Token test[b]	**20.5**	**14**	35.5	**28**	**32.5**	31.5	**20**	34.5	**12.5**	**28**	**14**	**15.5**	29.5	**19.5**	**25.5**	**28**
BNT[b]	**3**	**22**	**41**	42	**44**	53	**38**	48	**42**	49	**39**	**36**	46	**39**	41	54
Semantic fluency[b]	**1**	**0**	**13**	**13**	**14**	12	**6**	**13**	**4**	22	14	**5**	**6**	**5**	**7**	**13**
Phonemic fluency[b]	**2**	**1**	**4**	7	12	**6**	**5**	**2**	**1**	9	9	**1**	**3**	**3**	**4**	**5**

Word comp. = Word Comprehension; Comp. Id. Mat. = Complex ideational material; Sent. repetition = Sentence repetition.
[a] Scores in bold represent performance below the 50 percentile on the BDAE tests.
[b] Scores in bold represent performance below the normal limits (1.5 SD below the mean according to age- and education-adjusted norms for the Spanish population).

strings recalled in the next string length) (Shelton, Martin, & Yaffee, 1992).

Four composite scores were computed with the individual scores on the TALSA subtests. Composite *Phonological processing* included the phonological discrimination and rhyming judgment subtests, composite *Nonword repetition* comprised the nonword repetition subtests in both interval conditions and measured phonological STM with speech output, composite *Repetition span* involved the word and digit repetition spans measuring lexical-semantic STM with speech output, and composite *Pointing span* included the word and digit pointing spans addressing lexical-semantic STM without speech output. Note that although these two composite spans measure lexical-semantic STM, the relative weight of semantic involvement diverges from one another as they tap semantic and phonological components of lexical representations differently. That is, both spans access input phonological processes equally but diverge on output. In the pointing span tasks, access to lexical-semantics is obligatory as the endpoint of these tasks involves semantic representations including pictured concepts that correspond with the digits or words. Conversely, the repetition span tasks put more weight on access to lexical-phonological representations, because the endpoint of the task is verbal output, and access to lexical-semantics is optional as repetition can be achieved via access to phonological and lexical representations. Composites *Phonological processing* and *Nonword repetition* resulted from computing the average proportion of correct responses in all corresponding subtests, whereas composites *Pointing and Repetition span* represent the average span obtained in each of the measures involved. The composite scores of the participants with aphasia are presented in Tables 3 and 4.

In order to examine possible relationships between verbal STM and CSL in healthy adults, the older controls were also administered the TALSA subtests measuring verbal STM, and the composite measures *Nonword repetition*, *Repetition span* and *Pointing span* were computed for this group. Table 4 presents the performance of the older control group on these measures. The young adults were not administered these TALSA subtests because they are specifically developed for the assessment of language and verbal STM in PWA and healthy older individuals. Due to ceiling effects, these measures would not reliably reflect the true language or memory capacity of healthy younger individuals as they usually outperform older individuals in phonological processing and memory measures, and older healthy adults already reach high levels of performance on these measures.

2.3. *Experimental word learning tasks*

Both the CSL and the SL task were programmed on E-prime 2.0 (Psychology Software Tools. Inc., PA, USA). They were run on a laptop computer and auditory stimuli were presented through headphones. The order of task administration was randomized across participants. The detailed design of these tasks is provided below.

2.3.1. *CSL task*

The learning set included 9 black and white pictures of unknown objects (AFE paradigm, Laine & Salmelin, 2010) paired with 9 spoken bisyllabic pseudowords (hereafter words) created according to the Spanish phonotactics and recorded with a natural sounding male voice with the Loquendo 7 Multilanguage Text-to-speech Synthesizer (Nuance communications, MA, USA).

Fig. 1 depicts our experimental CSL task based on the one reported by Yu and Smith (2007). The task included 4 learning blocks (27 trials per block). Each learning block was followed by a 4-alternative forced-choice (4AFC) test (9 trials per test). The aim of our task design was twofold. Firstly, the initial part of the task including the first learning block and 4AFC test (hereafter CSL1) represents a pure measure of CSL with enough trials to observe learning with no performance-based feedback as in the original experiment reported by Yu and Smith (2007).[1] The second part of the task included three additional learning blocks and their respective 4AFC tests (CSL2, CSL3 and CSL4) in

[1] As compared to the original CSL experiment (Yu & Smith, 2007: 2 × 2 condition), our pure measure of CSL (i.e., CSL1) reduced to half both the learning set (from 18 to 9 words) and consequently the number of trials (from 54 to 27 trials), while maintaining the number of occurrences per word (i.e., 6 times) and the duration of each learning trial (6 sec). The learning set was reduced in order to reliably observe learning in the PWA while decreasing the difficulty and cognitive demands of the task.

Table 3 – Individual scores of the participants with aphasia in the TALSA battery composite measures tapping language and verbal STM.

TALSA composite measure	Cases															
	EV	CM	RG	RL	DM	JM	MS	JC	ON	AF	JH	AH	AI	MR	GB	JB
Phonological processing[a]	.72	.69	1	.87	1	.97	.97	.97	.92	.99	.94	.91	.8	.75	.92	1
Nonword repetition[a]	.33	.17	.67	.43	.08	.63	.37	.47	.3	.23	.07	.03	.4	.43	.67	.8
Repetition span[b]	3	2.3	5.1	3	6.4	5.3	3.3	4.8	1.9	5.3	3.2	3.1	3.3	4.2	3.7	5.2
Pointing span[b]	2.7	1.5	4.5	2.9	4.7	4.8	2.8	4.2	2.2	4.8	2.8	2.4	3.2	3.2	3.1	4.4

[a] Mean proportion of correct responses is provided.
[b] Average span is provided (the maximum span for all subtests is 7, the number of string length conditions).

Table 4 – Means and standard deviations of the participants with aphasia and the older controls on the verbal STM composite measures.

Group	TALSA: verbal STM composite measures		
	Nonword repetition[a]	Repetition Span[b]	Pointing Span[b]
Older controls	.66 (±.22)	5.49 (±.93)	5.41 (±.98)
Participants with aphasia	.42 (±.24)	3.94 (±1.27)	3.39 (±1.04)

[a] Mean proportion of correct responses is provided.
[b] Average span is provided (the maximum span for all subtests is 7, the number of string length conditions).

order to examine how the learning curves of the participants with aphasia evolved over time as compared to those of the older controls and the young adults. Nevertheless, learning across CSL2 through CSL4 may not be regarded as a pure measure of CSL as it could be influenced by carry-over effects from multiple testing (i.e., multiple testing may cue the correct word-referent associations by narrowing the possible referents for a given word presented in a test trial).

The structure of all four learning blocks was similar. In each learning trial, two novel objects simultaneously appeared on the left and right side of the screen separated by a fixation cross, while the two corresponding spoken labels (words) were presented over the headphones. At the beginning of each learning block, the participants were requested to carefully watch and listen as the learning trials were presented. They were told that 2 words and 2 pictures would co-occur on each trial and they were to figure out across trials which word goes with which picture. The duration of each learning trial was 6000 msec, including a 500 msec pause between words, and there was a 500 msec blank inter-stimulus interval. Each word-referent pair was presented 24 times across trials (6 times per block). Each word-referent pair co-occurred with every other word-referent pair at least once across the 108 learning trials (once per block and 3 times across all blocks). Therefore, the probability of co-occurrence between a given word and its correct referent was always 1.0 within and across learning blocks, while its probability of co-occurrence with any other irrelevant referent was always very low (.17 within the same block and .012 across learning blocks). The correspondence between word order (first *vs* second) and the position of the referent on the screen (left *vs* right) was counterbalanced across learning trials to avoid temporal or spatial cues on the word-referent relationships. The order of trials was pseudo-randomized and no performance feedback or indication as to which picture corresponded with which word was provided. The 4AFC test trials presented 1 spoken word and 4 objects of the learning set, and the participants were requested to point at the object to which

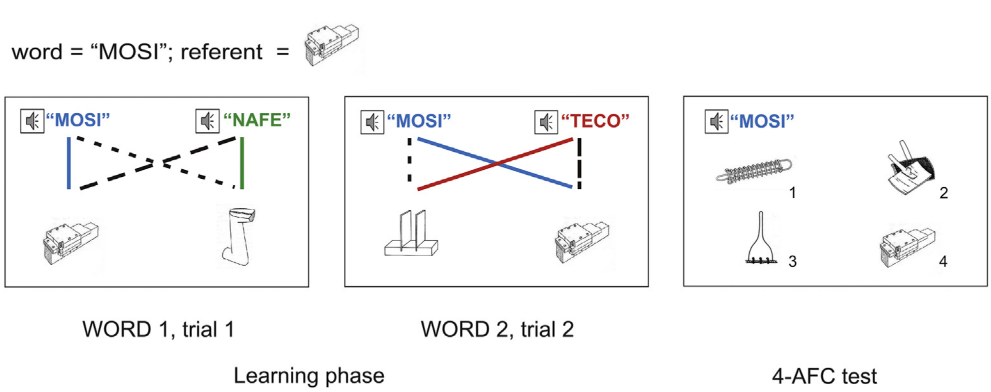

Fig. 1 – Design of the CSL task. Examples of the associations between word and referents in two individually ambiguous learning trials (i.e., solid colorful lines show the correct word-referent pairings across trials, and dashed lines show alternative yet incorrect word-referent pairings). In the example, learners can discover the correct referent for the word "MOSI" across learning trials, as individual trials do not provide reliable information as to which is the correct word-referent association. The figure also depicts a test trial where one spoken word is presented and the participant is to point at its corresponding referent amongst 4 referent candidates.

the word referred. The test was self-paced and the experimenter recorded all responses. There were altogether 36 testing trials, each word being tested 4 times.

Prior to the CSL task, the aphasic participants underwent a brief pre-exposure phase that involved a randomized auditory presentation of the 9 spoken words across 3 blocks. They were instructed to carefully listen to the words as they would need to perform another task with them at a later time. This was done to increase their sense of familiarity with the stimuli (Downes et al., 1997), so that their attention could be later focused on finding the correct word-referent associations instead of being driven by the novelty of the individual items presented on a single trial, as was observed in a pilot study.

2.3.2. SL task

We used an experimental task of speech segmentation via SL that we previously employed with people with chronic aphasia (Peñaloza et al., 2015). As in earlier SL studies (Saffran, Newport, et al., 1996), the participants were exposed to a small artificial language where the only cues to detect word boundaries were the transitional probabilities (TPs) between adjacent syllables (TP = 1 between syllables forming a word; TP = .33 between syllables spanning word boundaries). Four trisyllabic nonsense words phonotactically permissible in Spanish were designed and concatenated pseudo-randomly to create a 5.2 min speech stream (336 words in total, 84 repetitions per word). The language was generated with the MBROLA Speech synthesizer (Dutoit, Pagel, Pierret, Bataille, & van der Vreken, 1996) using a monotone male voice. The sequence was divided into two parts equated in duration and characteristics. The exposure was followed by a 2AFC test that required the discrimination of words of the novel language from nonwords (foils created with the syllables composing the language that were never concatenated together). The test included 16 word–nonword pairs, and the participants were to decide by button press whether the first or the second item of the pair was a word of the language. The items of each test pair were separated by a 400 msec pause. The order of presentation of the items was counterbalanced and the test pairs were randomized for each participant. The administration was self-paced. Prior to the speech segmentation task, the correct understanding of the 2AFC test was ensured by the administration of a training task that involved the exposure to 6 real words (3 bisyllabic and 3 trisyllabic tokens of different CV structure) and a brief 2AFC test on those words. Further details about this task are reported in Peñaloza et al. (2015).

2.3.3. Statistical analyses

The behavioral data corresponding to the CSL and SL tasks were available for all the participants, and only the nonword repetition span composite score of one participant in the older control group was unavailable for the analyses of the effects of verbal STM in the older controls. All statistical analyses were conducted using the statistical software package R (version 3.2.4).

In order to examine CSL ability in the participants with aphasia, the older controls, and the young adults, we analyzed the following two measures. First, as indicated in the Methods section, *CSL1* was our direct and pure measure of CSL, as was the case with Yu and Smith (2007). This allowed avoiding the possible carry-over effects of multiple testing in our experimental design, as repeated testing may influence the learning approach of the participants. The second measure was *overall learning performance* (proportion of correct responses across CSL1 − CSL4; 36 trials) which was intended to tap differences across groups in the evolution of their learning performance over time.

Group performance on the CSL and SL tasks was defined as being above chance level when .25 (CSL1) and .5 (SL) were outside the 95% CI for each group. We compared the mean proportion of correct responses of the three groups on CSL1 and on the SL task using a logistic regression with group as the categorical predictor. In these analyses the parameter estimates indicate pair-wise group comparisons. We expected to find superior learning performance for the older control and the young adult groups as compared to the aphasia group on both learning measures.

The learning curves were analyzed using multilevel logistic regression (growth curve analysis, GCA; Mirman, 2014) with a linear fixed effect of time (test number), categorical fixed effect of group, and, critically, their interaction. The model with a maximal random effect structure did not converge, so the random effects were reduced to just by-participant intercepts. Again, we expected to find superior and faster learning for the healthy participants relative to the participants with aphasia. In addition, the individual performance of each participant with aphasia on CSL1, their overall CSL performance, and their SL performance were contrasted against chance level using the binomial test (one-tailed) as we expected to identify some aphasic participants with above-chance level learning ability.

The relationship between CSL and SL was examined with a logistic regression. For this analysis we predicted a significant effect of SL on CSL1 in all three groups. Similarly, logistic regression was used to assess aphasia severity, phonological processing and verbal STM as potential predictors of CSL in the aphasic participants and to assess verbal STM as a potential predictor of CSL in the older controls. These analyses were conducted only on CSL1, as this represents a pure measure of CSL ability. Based on the previous literature on word learning in aphasia and the existing knowledge on the influence of memory on CSL in healthy individuals, we expected that all these variables would be significant predictors of CSL ability.

3. Results

3.1. CSL in PWA and neurologically healthy adults

3.1.1. Group differences in CSL

Fig. 2 shows the individual learning performance of the aphasic participants, the older controls and the young adults on CSL1. The performance of the young adults on CSL1 $M = .85$, 95% CI [.81, .88] was similar to that reported in the original experiment for the 2×2 condition (Yu & Smith, 2007: over 89% correct) and in a subsequent study with monolingual and bilingual learners employing the same condition (Poepsel & Weiss, 2016: monolingual English learners $M = 87\%$,

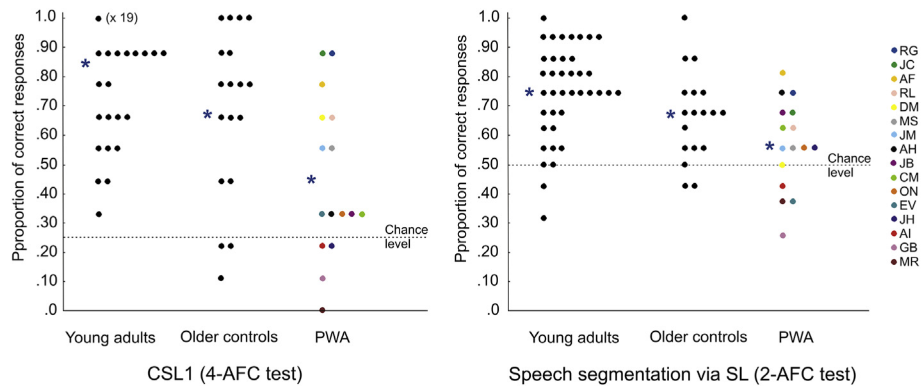

Fig. 2 – Individual learning performance of the participants with aphasia, older controls and young adults on the CSL task (CSL-1) and the SL task. Black dots represent each individual participant (except for "x 19" representing 19 young adults with maximum accuracy on CSL1) and blue asterisks represent the mean performance of each group in the learning tasks. Colorful dots represent PWA. Note that chance level differences across tasks are related to the number of response options provided in each test (CSL task: 4-AFC test, chance level = .25; SL task: 2-AFC test, chance level = .5).

SD = 17%; bilingual English-Spanish bilinguals M = 86.5%, SD = 11%). This successful replication supports the validity of our task design as a measure of CSL ability.

Table 5 shows the mean accuracy and 95% CI of each group on CSL1. The learning performances of the aphasia group, the older controls, and the young adults were all above chance on CSL1 (chance level = .25 for four-alternative choice tests). The logistic regression conducted to compare the performance of the three groups in CSL1 yielded a significant overall effect of group [χ^2 (2) = 80.85, $p < .001$], indicating significant differences in CSL performance between the three groups. Pairwise group comparisons revealed that each group was statistically significantly different from each other group. As expected, these comparisons revealed a significantly lower learning performance for the participants with aphasia as compared to the older controls (Estimate = −.973, SE = .238, $p < .001$) and the young adults (Estimate = 1.944, SE = .225, $p < .001$). Likewise, the learning performance of the older controls was significantly below the young adults (Estimate = .971, SE = .226, $p < .001$).

3.1.2. *Group differences in learning curves*

The overall CSL performance of the three groups across the four tests is presented in Fig. 3. We found a significant test number by group interaction [χ^2 (2) = 8.8, $p < .05$] indicating a significant difference between groups in the slope of the learning curves. The pairwise comparisons of the slopes showed that overall CSL performance in the aphasia group was marginally slower than in the older control group (Estimate = −.265, SE = .14, $p = .059$), and significantly slower than in the young adult group (Estimate = −.411, SE = .148, $p < .01$). The overall CSL performance of the older controls was non-significantly slower than in the young adults (Estimate = .146, SE = .163, $p = .37$).

3.1.3. *Individual differences in CSL performance in aphasia*

Exact binomial tests (one-tailed) examining performance on CSL1 at the individual level further revealed that 7 aphasic participants achieved above chance accuracy on CSL1 (performance ≥ 5/9 correct responses, $p < .05$ in all cases). The exact binomial tests (one-tailed) also indicated that the overall CSL performance of 9 aphasic participants was significantly above chance (performance ≥19/36 correct responses, $p < .001$ in all cases).

3.2. *Speech segmentation performance through SL*

3.2.1. *Group differences in SL*

The individual learning performances of the participants with aphasia, the older controls and the young adults on the SL task are depicted in Fig. 2. The accuracy of the young adults on the SL task M = .75, 95% CI [.72, .79] was similar to that reported for the young Spanish speaking participants in our previous experiment (Peñaloza et al., 2015: M = .73, SD = .14) and in the

Table 5 – Group means and 95% CI for accuracy on CSL and SL.

Group	CSL1			SL		
	Mean	Lower	Upper	Mean	Lower	Upper
Participants with aphasia	.4514	.3721	.5332	.5703	.5089	.6296
Older controls	.6852	.6097	.752	.6736	.6173	.7253
Young adults	.8519	.8107	.8853	.7548	.7195	.787

Reported values represent mean proportion of correct responses. .25 (CSL1) and .5 (SL) are outside the intervals for each group, indicating above chance level learning performance for all three groups.

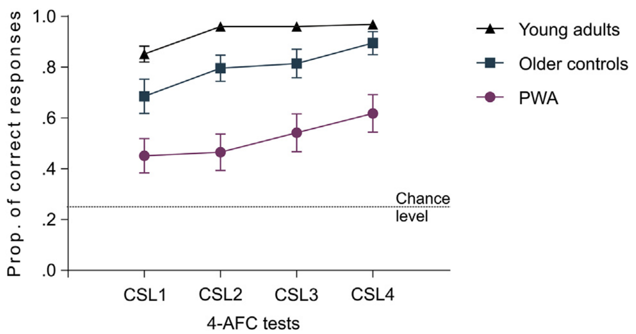

Fig. 3 – Group performance of the aphasia group, older controls and young adults in the CSL task. The Mean and SEM are depicted for each group across the four 4-AFC tests. Note that performance on the first part of the task (CSL-1) represents a pure measure of CSL without possible multiple-testing carry-over effects.

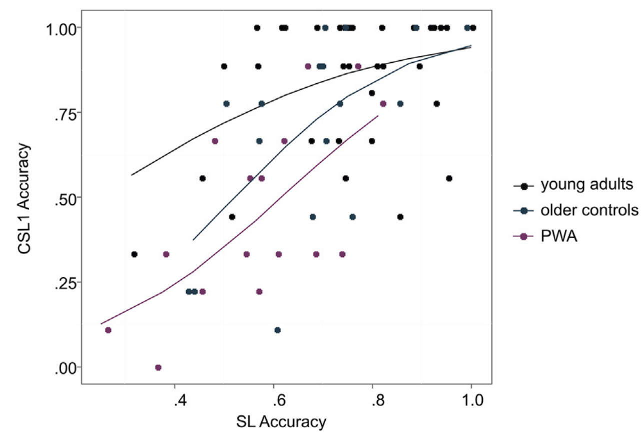

Fig. 4 – Effects of SL on CSL performance for the participants with aphasia, the older controls and young adults. The figure shows the individual performance of all the participants in the CSL task (CSL1) and the SL task measuring speech segmentation ability.

original SL study with healthy young adults (Saffran, Newport, et al., 1996: $M = 76\%$ correct). This replication supports the consistency of this task as a measure of SL ability.

Table 5 presents the mean accuracy and 95% CI of each group on speech segmentation by SL. The SL performances of the participants with aphasia, the older controls, and the young adults were all above chance (chance level = .5 for two-alternative choice tests). The logistic regression comparing performance accuracy in SL in the three groups revealed a significant effect of group [χ^2 (2) = 29.252, $p < .001$], indicating significant differences between groups in speech segmentation by SL.

Pairwise group comparisons evidenced that the SL performance of the aphasia group was significantly below that of the older controls (Estimate = −.441, SE = .178, $p < .05$) and the young adults (Estimate = .841, SE = .157, $p < .001$). The SL performance of the older controls was significantly below that of the young adults (Estimate = .4, SE = .156, $p < .05$).

3.2.2. *Individual differences in SL performance in aphasia*

The exact binomial test (one-tailed) indicated that three aphasic participants achieved significantly above chance segmentation performance (12/16 correct responses, $p < .05$ in all cases).

3.3. *Relationship between CSL and SL*

The logistic regression examining the relationship between CSL1 and SL in the aphasia group, the older controls, and the young adults revealed a strong effect of SL [χ^2 (1) = 105.484, $p < .001$] on CSL1 which did not interact with group [χ^2 (2) = 2.461, $p = .292$] suggesting a similar association between CSL1 and SL for all three groups. Fig. 4 depicts the effect of SL on CSL1 for the three groups. When tested separately for each group, the relationship between CSL1 and SL was significant for each group (in each of the cases $p < .001$: older controls, Estimate = 6.8, SE = 1.4; aphasia group, Estimate = 5.3, SE = 1.3; young controls, Estimate = 3.6, SE = .9). In the aphasia group, a subsequent logistic regression showed that the association between CSL1 and SL remained significant after controlling for aphasia severity [χ^2 (1) = 9.1, $p < .003$].

3.4. *Predictors of CSL in aphasia*

3.4.1. *Aphasia severity*

In order to examine the effect of aphasia severity on CSL in the aphasia group, the individual BDAE severity ratings were first added to the regression model as a fixed effect. Aphasia severity was a statistically significant predictor of CSL1 [χ^2 (1) = 12.24, $p < .001$] and a key variable to control for in the subsequent analysis of predictors of CSL in aphasia.

3.4.2. *Phonological processing and verbal STM*

Composite phonological processing and the following three measures of verbal STM were tested as possible predictors of CSL1 in aphasia: composite nonword repetition used to evaluate verbal phonological STM, repetition span measuring verbal lexical-semantic STM with phonological output, and pointing span tapping verbal lexical-semantic STM without phonological output. For the analysis of the aphasia group, aphasia severity was entered into the model first (i.e., controlling for aphasia severity), and then the predictors were tested individually for improvement on this baseline severity-only model. Due to the strong correlations between predictors and the limited sample size, it was not feasible to test unique effects of each predictor while controlling for all the others. As observed in Table 6, composites phonological processing, pointing and repetition span were significantly associated with CSL1 in aphasia; but this association became non-significant after controlling for aphasia severity. This indicates that the effects of our language and cognitive measures and those of overall aphasia severity on CSL were confounded.

3.5. *Effects of verbal STM on CSL in older adults*

Table 7 shows the relationships between all three measures of verbal STM and CSL1 in the healthy older controls. The logistic

Table 6 – Predictors of CSL1 performance in the participants with aphasia.

Variable	Before controlling for aphasia severity		After controlling for aphasia severity	
	χ^2 (1)	*p*-value	χ^2 (1)	*p*-value
Aphasia severity	12.24	<.001	–	–
Phonological processing	13.37	<.001	3.498	.061
Nonword repetition	2.109	.146	.001	.984
Pointing span	12.98	<.001	2.161	.141
Repetition span	9.596	.001	.477	.489

Tests of the individual effects of the composite scores before and after factoring out the effects of aphasia severity.

regression analysis revealed that all three composite measures of verbal STM were significant predictors of CSL1 in the older adults. As expected, composite pointing span and composite repetition span, both measuring lexical-semantic STM, were highly correlated with one another ($r = .940$, $p < .001$). Composite nonword repetition, which measured phonological STM was not significantly correlated with any measure of lexical-semantic STM (composite pointing span and composite repetition span, $p \geq .21$ in both cases). Therefore, we further tested for independent effects of phonological and lexical-semantic STM on CSL1. The effect of composite nonword repetition remained significant after controlling for lexical-semantic composites [χ^2 (1) = 9.70, $p < .01$]. Moreover, after controlling for composite nonword repetition, the effects of composite pointing span [χ^2 (1) = 9.59, $p < .01$] and composite repetition span [χ^2 (1) = 9.07, $p < .01$] on CSL1 also remained statistically significant. Therefore, the effects of phonological and lexical-semantic STM on CSL1 in the older adults can be considered as independent effects.

4. Discussion

The present study aimed to examine for the first time whether PWA can learn new word-referent mappings cross-situationally without feedback and how their learning ability evolved over time. Driven by the current theoretical debate on the possible mechanisms that support CSL in adults, we further studied whether CSL is associated with SL mechanisms in aphasic and neurologically intact adults. We also examined potential predictors of CSL ability in aphasia and in healthy older individuals.

Our logistic regression analyses showed that the CSL performance of the aphasic participants was inferior to that of the older controls and the young adults. However, the participants with aphasia were able to discover more word-referent pairs than expected by chance on CSL1, and their learning performance continued to increase towards the end of the task, albeit at a slower rate than in the older controls and the young adults. Moreover, individual case analyses indicated above chance learning for seven participants with aphasia in CSL1 and nine when considering overall learning performance. These findings indicate that the ability to learn new word-referent mappings can be achieved cross-situationally in some PWA even in the absence of performance feedback. This exceeds preliminary findings showing that some PWA can learn new word-object pairings in simple associative learning tasks (Kelly & Armstrong, 2009; Tuomiranta et al., 2012; Tuomiranta, Càmara, et al., 2014), in referentially ambiguous contexts supported by online feedback (Peñaloza et al., 2016), and in probabilistic associative learning tasks without feedback (Breitenstein et al., 2004). We also found that CSL performance in the aphasic participants was largely modulated by aphasia severity. Previous research has found a similar effect for aphasia severity on word-referent mapping through associative learning methods (Marshall et al., 2001), word-referent mapping under referential uncertainty (Peñaloza et al., 2016), and word re-learning through anomia therapy in PWA (Dignam et al., 2016). This suggests that cross-situational word learning is critically dependent on the integrity of language and cognitive resources in PWA.

We evidenced a strong association between SL and CSL1 performance in all three groups. This association provides further support to the SL account of CSL (Yu & Smith, 2007) which posits that human learners can solve the referential uncertainty of individual learning scenarios with various words and possible meanings by keeping track of the simultaneous co-occurrence of many words and referents across multiple learning instances. As evidence is accumulated across trials, they can gradually learn that the co-occurrence between some words and referents increase indicating correct word-referent associations, while the co-occurrences between words and other potential but erroneous meanings diminish. This is in line with several studies that indicate that healthy children and adults can learn word-referent mappings through cross-situational statistics (Smith & Yu, 2008; Smith, Smith, & Blythe, 2011; Suanda et al., 2014; Yu & Smith, 2007).

The present findings support the idea that cross-situational word learning and speech segmentation would at least partly rely on common SL mechanisms. SL is a mechanism that allows extracting regularities from the environment, enabling the cognitive system to discover the structure of a given input (Romberg & Saffran, 2010; Siegelman & Frost, 2015). In language learning, tracking statistical patterns can aid learners to gain knowledge about multiple aspects of the language structure such as word boundaries and meanings (for a review, see Saffran, 2003; Romberg & Saffran, 2010). In speech segmentation, SL allows isolating words from running speech through the computation of the statistical co-occurrences of sequential syllables which differ within and across boundaries in the language stream (Saffran, Aslin, et al., 1996; Saffran, Newport, et al., 1996). Likewise, in cross-situational word-referent mapping, SL can help resolving

Table 7 – Predictors of CSL1 performance in the older controls.

Variable	χ^2 (1)	*p*-value
Nonword repetition	17.68	<.001
Pointing span	17.63	<.001
Repetition span	15.78	<.001

referential ambiguity through the cross-trial computation of the co-occurrences of many words and referents (Yu & Smith, 2007). Although the statistical regularities computed are different across these two types of language input, our findings suggest that speech segmentation and meaning acquisition are not totally independent and that SL can be a common cognitive resource that supports rapid word learning. This is in line with evidence that segmenting words from speech precedes and facilitates the subsequent mapping of language sounds onto meanings (Graf Estes et al., 2007; Hay, Pelucchi, Graf Estes, & Saffran, 2011), and that learning can occur at both levels simultaneously (Cunillera, Càmara, et al., 2010; Cunillera, Laine et al., 2010; Räsänen & Rasilo, 2015; Thiesen, 2010), allowing learners to benefit from the synergic interaction of these two streams of information (Johnson, Frank, Demuth, & Jones, 2010).

Importantly, we found that both cross-situational word learning and speech segmentation can remain operative in some PWA even after damage to brain regions normally recruited for language processing. As in our previous studies of speech segmentation (Peñaloza et al., 2015) and word-referent mapping under referential uncertainty in aphasia (Peñaloza et al., 2016), our group-level analyses showed that the present aphasia cohort was above chance level on both word learning tasks, albeit inferior to their healthy older counterparts. Case-by-case analyses further indicated that learning performance across tasks remained functional in some PWA. Nevertheless, the SL effect in the present cohort of aphasic participants was not very strong relative to chance-level performance. It is worth noting that the learning performance of the aphasia group reported in an earlier study of SL (Peñaloza et al., 2015) was superior to the present one, with a likely reason being their overall more severe aphasia. In addition, CSL in the present sample was largely modulated by aphasia severity which also indicates that SL would be impaired in people with more severe aphasia. Importantly, while the present study examined SL employing verbal learning tasks, SL is a computational learning mechanism that is non-language specific (Schapiro & Turk-Browne, 2015) and previous research has shown that nonverbal probabilistic learning can be impaired in some PWA suggesting that general cognitive deficits or compromised neural systems supporting general cognitive mechanisms can affect learning ability in aphasia (Vallila-Rohter & Kiran, 2013).

Interestingly, past research suggests that SL ability can be constrained by verbal STM/working memory (WM) resources. Studies with healthy individuals have provided evidence in favor of the relationship between SL and verbal STM (Lopez-Barroso et al., 2011; Ludden & Gupta, 2000; Palmer & Mattys, 2016). Indeed, in a previous study about speech segmentation by SL in aphasia we found a significant correlation between SL and verbal STM (Peñaloza et al., 2015). Therefore, it is possible that the relationship between CSL and SL could be mediated by common cognitive processes such as verbal STM, as individual differences in verbal STM capacity might be a common source of variance in SL and CSL ability. We conducted a new logistic regression analysis to examine whether the relationship between CSL and SL in the healthy older adults was influenced by verbal STM capacity. This analysis showed that the association between CSL1 and SL remained significant after controlling for all three measures of verbal STM [χ^2 (1) = 17.7, $p < .001$]. However, the present aphasia data remains inconclusive due to an aphasia severity confound: after controlling for the considerable levels of severity in our aphasia cohort, the observed associations between STM measures and CSL were not significant anymore. As revealed by an additional regression analysis, this was also the case for the association between the verbal STM measures and SL in the aphasia group ($p > .19$ in all cases after controlling for aphasia severity). Nevertheless, the association between SL and CSL remained significant when aphasia severity was controlled for, thus ruling out verbal STM and aphasia severity as possible mediating factors in the strong SL-CSL relationship found in the aphasia group. Altogether, these findings indicate that SL mechanisms contribute to CSL beyond individual differences in verbal STM capacity.

It is also important to notice the strong association between verbal STM and CSL in the older adult group. All three composite measures of verbal STM were significant predictors of CSL1 and showed independent contributions of phonological and lexical-semantic verbal STM to word learning. Memory-based accounts of CSL suggest that the long-term retention of word-object mappings is affected by the degree of difficulty in retrieving information during learning which in turn may be modulated by STM (Vlach & Sandhofer, 2014). The involvement of STM processes in word learning is compatible with both the SL and the hypothesis testing accounts of CSL. Because both theoretical accounts of CSL imply that learners resolve referential ambiguity not on a single trial but across trials, it is likely that this condition alone places demands on STM. The characteristics and difficulty of the learning situation possibly modulate the STM load depending on: (i) the number of word-referent associations being learned, (ii) the number of word-referent associations presented per learning instance, (iii) the order of presentation of word learning instances, and (iv) how interleaved words appear across learning instances.

According to the statistical learning account of CSL (Yu & Smith, 2007), learning takes place simultaneously for multiple words and pictures, and even when learners cannot unambiguously decide what the correct word-referent associations are in a single learning instance, they should store possible word-referent mappings in STM across learning trials. This way they can gradually evaluate the statistical co-occurrences between words and referents to finally map each individual word to its corresponding referent. In the hypothesis testing view of CSL (Trueswell et al., 2013), learners generate hypotheses about the possible word-referent associations from the very beginning of the learning experience and such hypotheses are believed to be contrasted with further evidence to be confirmed or abandoned (and in the latter case, alternative hypotheses are elaborated). In this view, any given hypothesized pair would need to be retained in STM across trials at least until it can be confirmed or disconfirmed.

Our findings also concur with language-based models that propose a distinction between the phonological and lexical-semantic components of verbal STM (Freedman & Martin, 2001; Shivde & Thompson-Schill, 2004). Past research of word learning in PWA has shown that the long-term learning of phonological and semantic representations is constrained by phonological and lexical-semantic STM capacity respectively (Freedman & Martin, 2001). Moreover, there is evidence that these aspects of verbal STM also can modulate word learning under referential ambiguity beyond aphasia severity (Peñaloza et al., 2016). In the aphasia group reported here, the association between verbal STM and CSL was also initially found for the pointing and repetition spans, two composite measures of lexical-semantic STM, although these associations became non-significant after factoring out aphasia severity. However, the aphasic participants in the current sample were more severely affected than the ones reported in Peñaloza et al. (2016). Moreover, most of them had damage to left frontal regions which may have obscured the effect of verbal STM on CSL that was otherwise clearly evidenced in the older controls. The left inferior frontal region has been attributed a role in verbal STM (Martin, 2005; Shivde & Anderson, 2011) and verbal and non-verbal SL (for a review see Arciuli & von Koss Torkildsen, 2012; Uddén & Bahlmann, 2012). It has been shown that lesions that involve the left frontal region may impair both verbal STM and word learning under referential ambiguity in aphasia (Peñaloza et al., 2016). Moreover, there is evidence that PWA with frontal damage can show impaired performance in phoneme sequential learning (Goschke, Friederici, Kotz, & van Kampen, 2001), in SL tasks tapping speech segmentation (Peñaloza et al., 2015), and artificial grammar learning (Christiansen, Louise Kelly, Shillcock, & Greenfield, 2010; Zimmerer, Cowell, & Varley, 2014). However, in the present aphasia cohort where the left frontal lobe was affected in all but three individuals, aphasia severity and specific verbal STM effects could be confounded. Although the effects of verbal STM on CSL seemed evident in the older adults and in the aphasia group, these effects were not assessed in the young adults because they were expected to reach ceiling effects on subtests developed for aphasic speakers. Future studies will need to determine whether these effects are also observed in younger adults and whether the effects of verbal STM on CSL are independent from frontal damage in PWA.

While we found that learners may at least partially rely on SL mechanisms to disambiguate word-referent associations in CSL and that verbal STM resources can modulate this ability, our findings do not reject the possibility that other strategies are also involved in this learning process. For instance, learners may use eliminative or frequentist approaches depending on the degree of referential uncertainty (Smith et al., 2011). Also, our results do not prove against the hypothesis testing account of CSL which presumably is also compatible with the engagement of STM processes. In fact, it has been proposed that statistical associative learning and hypothesis testing may fall on the same continuum of learning strategies (Roembke & McMurray, 2016; Yu, Smith, Klein, & Shiffrin, 2007) and that such combination may even entail competition (Yurovsky, Yu, & Smith, 2013) and inferential processes including mutual exclusivity (Roembke & McMurray, 2016).

The present study also contributes to our current knowledge regarding the effects of aging in SL, which has been addressed in only a few previous studies. Although learning performance in the older controls was above chance level, the young adults showed a clear advantage in both the speech segmentation and the CSL task. Older people present age-related deficits in learning tasks of higher-order sequences that involve non-adjacent dependencies of visual shapes (Feeney, Howard, & Howard, 2002; Howard & Howard, 1997) and spoken words (Dennis, Howard, & Howard, 2003) when compared to young adults. They are also usually outperformed by young adults in tasks that involve learning word-referent pairs in associative (Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003) and fast-mapping paradigms (Greve, Cooper, & Henson, 2014), as well as under referential ambiguity (Peñaloza et al., 2016). It has been proposed that overall SL ability may decline in older adulthood due to impaired memory and sensory-related resources (Daltrozzo & Conway, 2014). Furthermore, young adults are more efficient in employing different associative learning strategies than older adults (Naveh-Benjamin, Brav, & Levy, 2007) who are less effective in binding and retrieving links between single information units (Naveh-Benjamin, 2000). Our results support the view that SL mechanisms can contribute to effective speech segmentation and CSL throughout the adult lifespan, with fast and robust learning in young adulthood and still effective but decreased learning capacity in the elderly.

Some potential limitations are worth considering in the present study. The number of testing trials included in the CSL1 and SL measures was quite limited. For this reason, although the validation of the tasks with the young adults replicated the findings from previous studies and the participants with aphasia showed above chance learning performance as a group, our findings should be regarded as preliminary. Also, our design only took into account the final outcome of learning performance and we did not evaluate how learning accuracy unfolded across individual learning trials. This approach would have allowed for a closer inspection into how participants solve the referential ambiguity exposure to exposure. Our repeated-testing design has been used previously in CSL research (i.e.: Smith et al., 2011), and it allowed examining and evidencing incremental learning ability in the aphasic participants. However, performance across these tests may not be taken as a pure measure of CSL as it may have also influenced the participants' learning approach to the task. Repeated testing may have narrowed down the referential ambiguity initially presented and even promoted retrieval practice and increase long-term learning (Roediger & Buttler, 2011). Future research on CSL in aphasia should increase the reliability of the measures reported here by including a larger number of testing trials and consider methodological approaches that allow for more pure forms of testing learning ability, while reducing high cognitive demands for aphasic individuals. Eye-tracking methods used in previous CSL studies in healthy individuals (e.g., Trueswell et al., 2013; Roembke & McMurray, 2016) could prove a suitable approach for this purpose.

Also, there was some variability in the language background of our overall sample as the aphasia group mostly included Spanish monolinguals, while the older and younger healthy adults were mostly Spanish/Catalan bilinguals. Addressing the effects of native language and bilingualism in the word learning ability of PWA was beyond the scope of our study. However, it has been recently demonstrated that healthy adult monolingual and bilingual speakers do not significantly differ in their CSL ability under minimal referential ambiguity (Poepsel & Weiss, 2016). Future research should examine the influence of linguistic background in new word learning in aphasia and determine whether the differences in learning ability found between PWA and healthy individuals are also associated to native language and bilingualism.

5. Conclusions

Our findings indicate that new word-referent mapping in aphasia can be achieved cross-situationally, and that SL mechanisms and verbal STM resources may support this learning ability in both healthy and aphasic individuals. We suggest that both speech segmentation and cross-situational word learning ability engage common SL mechanisms. The availability of cognitive resources that support the effective evaluation of language regularities in complex learning environments may be crucial for new word learning across the adult lifespan, also in the presence of brain damage.

Conflict of interest

The authors declare no competing financial interests.

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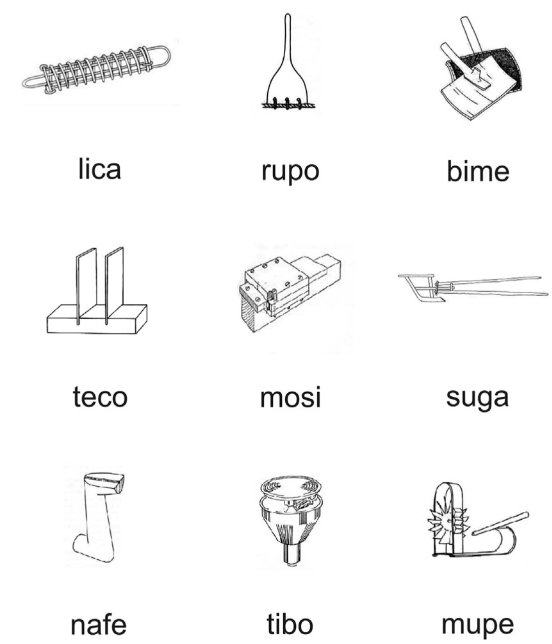
Appendix A. Words and pictures used in the CSL task.



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