ANNAMÁRIA KISS[1] – VALÉRIA CSÉPE[2, 3]

[1]Multilingualism Doctoral School, University of Pannonia
annamaria.kiss@phd.uni-pannon.hu
https://orcid.org/0009-0009-1194-0341

[2]HUN-REN RCNS Brain Imaging Centre
[3]University of Pannonia
csepe.valeria@ttk.hu
https://orcid.org/0000-0002-5021-6024

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Investigating working memory impairments in bilingual aphasia

While most aphasia studies investigate working memory impairments in monolinguals, there is a lesser focus on bilinguals. This study aimed to compare the assumed working memory impairments in individuals with monolingual and bilingual aphasia. Therefore, the study employed both visual and verbal working memory tasks, including the Visual Sequential Memory Test, the Rey-Osterrieth Complex Figure B, and the Auditory Sequential Memory Test. It was hypothesised that both aphasia groups would exhibit impairments in their visual and verbal working memory performance. A total of 54 participants were recruited, including monolingual (N=10) and bilingual (N=8) individuals with aphasia as well as individuals without any neurological problems(N=36). Both aphasia groups demonstrated significant variability in the visual and auditory memory tasks, with impairments noted in comparison to the reference groups. Although the bilingual aphasia group had lower scores than the monolinguals, these differences were not statistically significant. These findings contribute to our understanding of the less explored domain of working memory impairments in bilingual aphasia.

Keywords: aphasia, bilingual aphasia, working memory impairment, visual and auditory working memory, multiple case study

1. Introduction

Aphasia, a language disorder resulting from brain damage, presents unique challenges in understanding the cognitive processes underlying language impairment. Although extensive research has focused on working memory deficits in monolingual individuals with aphasia, less attention has been paid to those shown by bilingual aphasics. Therefore, there is a significant gap in the relevant literature regarding the characteristics of their working memory, a system responsible for temporal holding and manipulating information, which is crucial for language processing and communication. This study aims to bridge this gap by providing data acquired by testing working memory in monolingual and bilingual individuals with aphasia.

1.1. Aphasia

Aphasia is regarded as an acquired language disorder following brain damage, leading to impairments in all language modalities (Chapey, 2008). According to the multidimensional view, multiple forms of aphasia exist, all influenced by and corresponding to distinct underlying lesion sites that exhibit individual characteristics (Goetz, 2007). A broadly accepted distinction is made between fluent (Wernicke's, conduction, transcortical sensory, and anomic) and non-fluent (Broca's, global, transcortical motor, and mixed transcortical) subtypes of aphasia. The main characteristics of subtypes (*non-fluent with Italic*) of aphasia are presented in Table 1.

Table 1. Main characteristics of subtypes of aphasia

Aphasia type	Speech	Comprehension	Repetition	Naming
Wernicke's	fluent, empty	poor	poor	poor
Conduction	fluent	good	poor	poor
Transcortical sensory	fluent	poor	good	poor
Anomic	fluent with circumlocutions	good	good	poor
Broca's	*poor*	*good*	*poor*	*poor*
Global	*extremely poor*	*poor*	*poor*	*poor*
Transcortical motor	*little*	*good*	*good*	*poor*
Mixed transcortical	*extremely poor*	*poor*	*good*	*poor*

1.2. Bilingual Aphasia

Bilingual aphasia is a condition in which an individual who is fluent in two or more languages experiences language deficits in both languages following brain damage. This condition presents unique challenges for assessment, diagnosis, and treatment due to the complex interaction between the two languages in the brain. Bilingual aphasia can be classified into two types of impairments: parallel and selective. Parallel impairment occurs when both languages of a bilingual person are affected to a similar extent. Selective impairment, on the other hand, refers to a situation where one language is more affected than the other (Gitterman et al., 2012).

1.3. Working memory in aphasia

Working memory (WM) is defined as a system of limited capacity that is responsible for holding and manipulating information while undertaking cognitive tasks (Baddeley, 2003). Most studies investigating the working memory of individuals with monolingual aphasia have consistently shown an impairment in updating (Murray et al., 2001; Wright & Shisler, 2005; Potagas et al., 2011; Mayer & Murray, 2012). However, it is notable that many studies have employed linguistically demanding tasks. To complete these tasks, individuals must engage in semantic and/or phonological processing, enabling them to understand the instructions and formulate an appropriate response. Some studies have focused on investigating non-linguistic working memory, with particular attention paid to ensure the tasks were simple and fully non-linguistic (Christensen & Wright, 2010; Christensen et al., 2018)

Christensen and Wright (2010) conducted a study examining both linguistic and non-linguistic working memory in a sample of 12 monolingual individuals with aphasia whose language impairments varied as measured by the Aphasia Quotient (AQ) of the Western Aphasia Battery (WAB), with scores ranging from 47.9 to 90.7. The researchers employed the *n*-back task using three distinct categories of stimuli, different in terms of linguistic load. This linguistic load refers to the semantic and phonological variations of the stimuli. The category "fruit" represented the highest linguistic load, fribbles, e.g., novel objects could be classified as semi-linguistic while blocks were classified as non-linguistic stimuli. The Christensen and Wright study (2010) suggested that the working memory performance was significantly improved by verbal encoding, especially in aphasic participants. Their findings indicate that aphasic participants demonstrated a similarity in performance with the control group regarding WM tasks that varied according to linguistic load, though the performance of aphasics was limited. It was also observed that decreasing the linguistic elements of the task resulted in a decrease in the performance accuracy of aphasic participants.

In a later study, Christensen et al. (2018) investigated WM impairments in aphasia. The study involved 14 individuals with aphasia and compared their performance with 13 control participants. To measure WM impairments, the study employed verbal and spatial *n*-back tasks, the Flanker test, as well as forward digit and spatial tasks. For the verbal task, the study employed the verbal *n*-back task, which included letters. For the spatial task, the study used an *n*-back task with black circles. Christensen et al.'s (2018) study revealed that aphasic participants demonstrated poorer performance in the verbal tasks compared to the control group. However, in spatial tasks, both groups performed similarly, suggesting that aphasics tend to exhibit significant challenges in WM in the context of verbal tasks. The study also indicated that impairments in verbal WM in aphasics could be due to inhibition problems, e.g., an inability to suppress irrelevant information, which might also play a role in working memory deficits.

In addition to investigating non-linguistic working memory in individuals with aphasia, recent studies have focused on the efficacy of WM training in aphasia. For example, Zakariás et al. (2018) investigated whether the benefits of computerised WM training would help to improve not only the participants' working memory skills but also auditory comprehension. The training targeted various components of working memory. The study involved three individuals with aphasia in the chronic phase of recovery. The results showed that aphasics demonstrated some improvement regarding at least one measure of auditory comprehension and everyday memory tasks. Moreover, two aphasics exhibited some improvement in measures of working memory and functional communication skills. Zakariás et al.'s (2018) study revealed that the WM performance could be enhanced by a computer-based training in the chronic stage of recovery in individuals diagnosed with aphasia.

Furthermore, Nikravesh et al. (2021) investigated how WM training affects people with aphasia in memory and language performance. The study involved 13 participants diagnosed with aphasia with moderate and mild symptoms. Their findings revealed that individuals with aphasia exhibited notable improvements in memory tasks. Additionally, the language performance of individuals with aphasia improved as well, suggesting that working memory training could be beneficial not only for memory but also for language abilities in individuals with aphasia.

1.4. Working memory in bilingual aphasia

Data on the updating component of WM in bilingual aphasics are limited (Penn et al., 2009; Adrover-Roig et al., 2011; Lee et al., 2016; Penn et al., 2017) and of mixed outcome.

The preliminary study of Penn et al. (2009) investigated impairments in updating in bilinguals with aphasia in the chronic stage of recovery. The study involved two bilingual and eight monolingual aphasics with mild and moderate symptoms. The Working Memory Self-Ordered Pointing Test used by the authors did not reveal impairments in the two bilingual patients, whereas impaired updating was demonstrated in the eight monolingual aphasics.

Furthermore, Adrover–Roig et al. (2011) have investigated a 53-year-old right-handed Basque-Spanish bilingual male who had a haemorrhagic incident of stroke. The patient, at the time of investigation, was in the chronic stage of his recovery and showed selective impairment, e.g., his L2 was more intelligible than his L1, even after 3 months of speech therapy in both languages. The brain damage in the patient was restricted to the left basal ganglia, resulting in impairments in his L1 to a larger extent. The language assessment tools included the Bilingual Aphasia Test and the Boston Naming Test in both languages. The executive function assessments included the forward and backward digit span tasks, the classical Stroop test, and the Trail Making Test (TMT). The results of these executive function assessments revealed impairments in updating, inhibition, and shifting.

Lee et al. (2016) described the impairments of a bilingual patient with crossed aphasia, a rare case in dextrals, e.g., a right hemispheric lesion in a right-handed person. The 47-year-old male patient had an extensive haemorrhage in the right basal ganglia. The investigation utilized the Western Aphasia Battery (WAB), which was administered in the subacute stage of recovery and later in the chronic stage, following a six-month course. This resulted in balanced proficiency in both languages, with equal abilities in the L1 (Korean) and L2 (Japanese). The WAB was employed in both languages, with AQ scores of 32.0 for Korean and 50.6 for Japanese, respectively. Based on the WAB results, the patient was diagnosed with Broca's aphasia. The fMRI (functional Magnetic Resonance Imaging) study revealed left lateralised activation in both language tasks, especially in the inferior frontal gyrus. The non-linguistic assessments were conducted in the subacute stage using a range of tests, including the digit span task, the TMT, the Rey Complex Figure Test, and the Wisconsin Card Sorting Test (WCST). The results of these tests revealed multiple impairments in the subacute stage of recovery, including inhibition, updating, and shifting. Lee et al. (2016) revealed that, despite the absence of a follow-up assessment of the executive functions in the chronic stage, repetition of the WAB and the naming test showed no sign of the paradoxical pattern of bilingual aphasia.

Finally, Penn et al. (2017) investigated the recovery patterns during the acute and subacute stages of recovery in post-stroke participants with bilingual aphasia (N = 10). The ten aphasic patients (seven males and three females aged 27-65 years) with different sites of and types of aphasia were tested over two periods of time within the first 12 weeks following the incident leading to severe symptoms of aphasia. The control group consisted of 19 neurologically intact bilingual individuals (6 males and 13 females) and was matched as closely as possible to the aphasic patients in terms of age, level of education, and linguistic variety. Penn et al.'s (2017) study revealed impaired updating, as tested by a non-linguistic n-back task, in individuals with aphasia. It is, however, noteworthy that they exhibited impairment both in the acute and subacute stages of recovery.

1.5. The present study

The present study aimed to investigate working memory impairments in individuals with monolingual and bilingual aphasia. Therefore, visual and auditory working memory tasks were employed.

Our first hypothesis was that participants with aphasia would demonstrate impaired working memory in the visual domains. To identify the expected impairments, the Visual Sequential Memory Test and the Rey-Osterrieth Complex Figure B Test were employed.

Our second hypothesis was that verbal working memory impairments would be identified by using the Auditory Sequential Memory Test.

Our third hypothesis was that bilinguals with aphasia would perform better in working memory tests than monolingual aphasics.

Our fourth hypothesis was that significant performance differences would be found between aphasic participants and neurologically healthy participants, serving as a matched reference, for both bilinguals and monolinguals.

2. Methods

2.1. Participants

The study aimed to investigate working memory capabilities of individuals with monolingual and bilingual aphasia and compare with neurologically intact mono- and bilingual participants as a reference. A total of 54 participants were recruited for this study, divided into four groups: monolingual people with aphasia (mPWA), bilingual people with aphasia (bPWA), monolingual healthy participants (mHP), and bilingual healthy participants (bHP), all of whom had no neurological diagnosis. All bilingual participants have used the two languages in parallel. All participants provided informed consent, and the confidentiality of their data was maintained through the anonymization process, which involved assigning a unique identification number to each participant. Participants were informed of their right to withdraw from the study at any time without consequences. Tables 2 and 3 present the basic demographic data (age, sex, years of education) and clinical data of aphasic patients. Tables 4 and 5 present the basic data for the reference groups. Data on L1 and L2, as well as the age of acquisition, are presented in Tables 3 and 5.

2.1.1. Aphasia groups

All participants with aphasia had suffered a cerebrovascular accident. Clinical criteria for aphasic participants included: (1) signs of aphasia as indicated by their performance during the WAB test, (2) at least 6 months post-onset of their stroke, and (3) premorbid right-handedness.

Table 2. Demographic data of the monolingual aphasia group

Participants	Age	Sex	Education in years	Post-onset days	Speech	Lesion site	Aphasia severity
mPWA1	49	female	11	395	non-fluent	left	severe
mPWA2	76	male	11	556	fluent	left	mild
mPWA3	71	male	11	181	fluent	right and left	mild
mPWA4	63	male	11	183	non-fluent	left	severe
mPWA5	71	male	11	10717	fluent	left	mild
mPWA6	69	female	16	6162	fluent	left	mild
mPWA7	61	male	11	2363	non-fluent	left	severe
mPWA8	83	female	11	278	fluent	left	mild
mPWA9	64	male	22	730	fluent	left	mild
mPWA10	80	female	12	183	fluent	left	moderate
Mean	68.7		12.7	2174.8			
SD	9.99		3.62	3532.16			
min-max	49-83		11-22	181-10717			

The monolingual aphasia group consisted of 10 participants. The demographic data for this group is summarised in Table 2. Participants ranged in age from 49 to 83 years, with a mean age of 68.7 years (SD = 9.99). The group comprised six males and four females, all of whom had completed 11 to 22 years of education, with a mean education level of 12.7 years (SD = 3.62). The duration of post-onset days varied among participants, ranging from 181 to 10,717 days, with a mean of 2174.8 days (SD = 3532.16). Speech characteristics varied, with some participants exhibiting fluent speech (N = 7) and others classified as non-fluent (N = 3). Lesion sites were predominantly located in the left hemisphere, and aphasia severity ranged from severe to mild.

Table 3. Demographic data of the bilingual aphasia group

Participants	Age	Sex	Education in years	Post-onset days	Speech	Lesion site	Aphasia severity (parallel)	L1	AoA L1	L2	AoA L2
bPWA1	73	female	12	8580	fluent	left	mild	CRO	from birth	HU	6
bPWA2	72	female	16	603	fluent	left	mild	CRO	from birth	HU	6
bPWA3	57	male	12	8978	fluent	left	mild	CRO	from birth	HU	3
bPWA4	60	male	11	369	fluent	left	mild	HU	from birth	DE	30
bPWA5	49	female	20	225	fluent	left	mild	HU	from birth	SK	3
bPWA6	72	male	11	201	non-fluent	left	severe	HU	from birth	SK	6
bPWA7	44	female	14	1989	fluent	left	moderate	HU	from birth	SK	3
bPWA8	81	female	11	184	non-fluent	left	severe	HU	from birth	SK	6
Mean	63.5		13.38	2641.13							7.88
SD	13.02		3.20	3835.87							9.06
min-max	44-81		11-20	184-8978							3-30

The bilingual aphasia group consisted of 8 participants, with demographic details presented in Table 3. Participants' ages ranged from 44 to 81 years, with a mean age of 63.5 years (SD = 13.02). This group included three males and five females, with educational backgrounds ranging from 11 to 20 years (mean = 13.38 years, SD = 3.20). The post-onset days varied from 184 to 8978 days, with a mean of 2641.13 days (SD = 3835.87). Six participants reported fluency in their speech, and two individuals were classified as non-fluent. The participants had Croatian (CRO) or Hungarian (HU) as their first language (L1) and had acquired their second language (L2), which was either Hungarian, Slovakian (SK), or German (DE), at varying ages.

2.1.2. Reference groups

The healthy monolingual group consisted of 18 participants, with their demographic data summarised in Table 4. Participants' ages ranged from 45 to 85 years, with a mean age of 67.67 years (SD = 10.99), which is highly comparable with the aphasia group. This group consisted of 8 males and 10 females, with education levels ranging from 8 to 22 years (mean = 13.28 years, SD = 3.63). This group served as a reference for the monolingual aphasia group.

Table 4. Demographic data of the healthy monolingual participants

Participants	Age	Sex	Education in years
mHP1	70	female	14
mHP2	71	male	11
mHP3	72	female	16
mHP4	75	female	8
mHP5	66	male	11
mHP6	64	female	11
mHP7	63	female	15
mHP8	63	male	11
mHP9	65	female	12
mHP10	45	female	16.5
mHP11	85	male	8
mHP12	64	male	14
mHP13	48	female	16
mHP14	58	male	15.5
mHP15	75	male	14
mHP16	85	female	8
mHP17	83	female	16
mHP18	66	male	22
Mean	67.67		13.28
SD	10.99		3.63
min -max	45-85		8-22

The healthy bilingual group consisted of 18 participants, whose demographic characteristics are presented in Table 5. Participants' ages ranged from 46 to 80 years, with a mean age of 65 years (SD = 9.80). The group consisted of 13 females and five males, with educational attainment ranging from 8 to 30 years (mean = 13.17 years, SD = 5.51). Similarly to the bilingual aphasia group, the participants had their first language (L1) as Croatian (CRO) or Hungarian (HU) and had acquired their second language (L2), which was either Hungarian, Croatian, Slovakian (SK), or German (DE), at varying ages. This group served as a reference for the bilingual aphasia group.

Table 5. Demographic data of the healthy bilingual participants

Participants	Age	Sex	Education in years	L1	AoA L1	L2	AoA L2
bHP1	62	female	12	CRO	from birth	HU	3
bHP2	63	female	11	CRO	from birth	HU	3
bHP3	66	female	16	CRO	from birth	HU	3
bHP4	66	female	14	CRO	from birth	HU	6
bHP5	67	female	8	CRO	from birth	HU	6
bHP6	67	female	16	CRO	from birth	HU	6
bHP7	71	female	8	CRO	from birth	HU	3
bHP8	72	male	8	CRO	from birth	HU	3
bHP9	72	male	11	CRO	from birth	HU	6
bHP10	76	female	8	CRO	from birth	HU	6
bHP11	77	female	11	CRO	from birth	HU	6
bHP12	69	male	11	HU	from birth	DE	30
bHP13	50	female	18	HU	from birth	SK	from birth
bHP14	80	female	8	CRO	from birth	HU	6
bHP15	60	female	30	HU	from birth	CRO	from birth
bHP16	46	female	18	HU	from birth	CRO	from birth
bHP17	47	male	17	CRO	from birth	HU	3
bHP18	59	male	12	HU	from birth	CRO	23
Mean	65		13.17				6.28
SD	9.80		5.51				7.77
min-max	46-80		8-30				0-30

2.2. Procedures

Participants with aphasia were recruited from various sources. The recruitment was conducted via three principal channels: (a) institutional, (b) private speech and language therapists, and (c) individuals.

(a) Institutional recruitment: Some participants were recruited from rehabilitation centres and hospitals, approached in collaboration with rehabilitation departments where speech therapists identified suitable candidates based on predefined inclusion criteria.

The individuals bPWA2, mPWA2, and mPWA7 were recruited from the Sopron Erzsébet Teaching Hospital and Rehabilitation Institute in Hungary (Soproni Erzsébet Oktató Kórház és Rehabilitációs Intézet). The hospital provided a speech therapist, a bilingual psychologist for the Croatian tests, and a quiet, private room for the assessments. The speech therapist conducted the Hungarian tests with bPWA2, mPWA2, and mPWA7, while the bilingual psychologist carried out the Croatian tests with bPWA2. Both the Hungarian and Croatian assessments were conducted in the presence of the author of this study. The hospital director of the Rehabilitation Institute in Sopron granted written permission (reference number: 543-2/2023) for the first author of this study to enter the Institution and utilise the speech therapy room to conduct assessments.

Participant bPWA5 was recruited from Penta Hospitals (Nemocnica Dunajská Streda) in Slovakia. The director of the hospital gave written authorisation to the first author of this study to enter the Institution and use the speech therapy room to conduct assessments. The hospital provided a speech therapist and a suitable room for the assessments. Since the speech therapist was bilingual (L1 Hungarian, L2 Slovakian), all the tests were conducted in the presence of the speech therapist and the author of this study.

(b) Private Speech Therapists: Additional participants were recruited through private speech therapists. These professionals were contacted to identify individuals who are actively seeking therapy and meet the study's eligibility requirements. Written informed consent was obtained from both therapists and participants prior to collecting data. Individuals bPWA6, bPWA7, and bPWA8 were recruited from a private speech therapist in Slovakia, while individuals mPWA8, mPWA9, and mPWA10 were recruited from a private speech therapist in Hungary.

(c) Individual recruitment: A subset of participants was recruited on an individual basis, particularly those who had completed a course of formal speech therapy and were no longer receiving regular treatment. These individuals were approached directly, often through community outreach or support groups for people with aphasia. Data for this group was collected in their homes to ensure a comfortable and familiar environment, thereby facilitating a more effective assessment. The following participants were recruited individually: bPWA1, bPWA3, bPWA4, mPWA1, mPWA3, mPWA4, mPWA5, and mPWA6. All participants provided written informed consent.

Due to the length of the tests, the examinations were performed in several sessions. Every participant was tested individually. All procedures were conducted in accordance with ethical guidelines, ensuring that the participants were fully informed of the study's purpose and their right to withdraw their participation at any time.

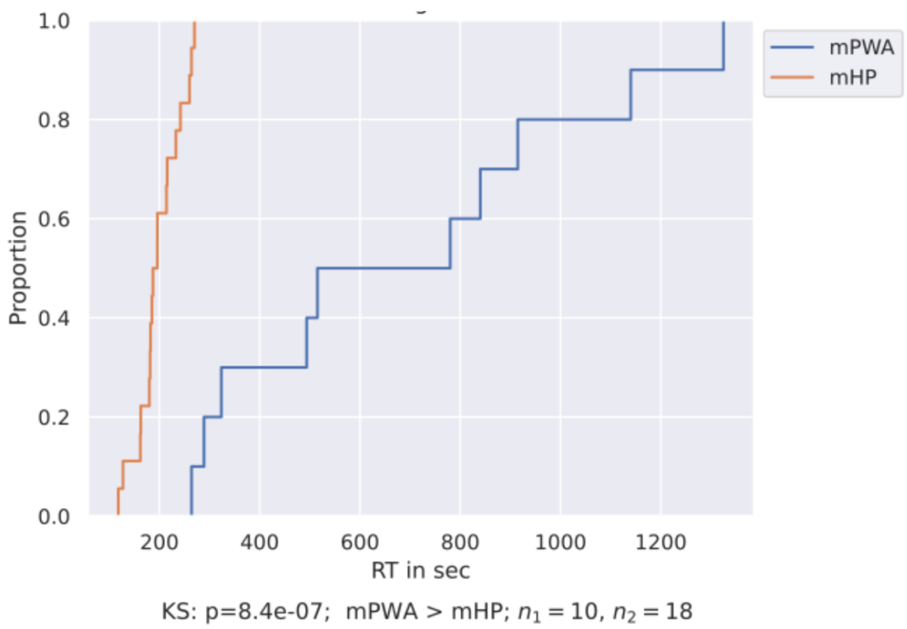
2.3. Data analysis

The Kolmogorov-Smirnov (KS) test, a non-parametric and distribution-free test that imposes no assumptions regarding the underlying data distribution, was used. Specifically, the two-sample KS test with a one-sided alternative hypothesis for stochastic dominance was employed. Unlike the Mann–Whitney U test, which primarily evaluates differences in central tendencies between two populations, the KS test considers the entire distribution of data (Dodge, 2008). In the case of discrete data, the KS test tends to be conservative, as noted in previous studies (Noether, 1963; Slakter, 1965; Walsh, 1963). We conducted our analysis using the SciPy library's implementation (Virtanen et al., 2020), specifically with the kstest function.

The empirical cumulative distribution function (ECDF) is a useful statistical tool for visualising the distribution of data points in a dataset. In our study, ECDF plots were used to illustrate the differences in performance between individuals with bilingual and monolingual aphasia as well as between individuals with aphasia and healthy participants.

Figure 1 illustrates an example of an ECDF graph, where the x-axis represents the values of the variable being studied, e.g., response time or test scores. The y-axis represents the cumulative proportion of participants scoring at or below a given score. For instance, a point on the stepped line at 0.6 indicates 60% of the observations fall below this value. The line rises in steps, with each step corresponding to an observation in the dataset. In our example (Figure 1), we compare two groups: individuals with monolingual aphasia (mPWA) and healthy monolingual participants (mHP) in a task that assesses performance differences in response time between the two groups. It can be seen in the example that the p-value and mPWA > mHP are included in the figure. The relation sign means that the mPWA group produced greater numerical data compared to the mHP group. It is important to note that the stepped line of the group with the greater numerical data is constantly situated below the other line. The steepness of the lines can also provide insight into the variability of performance within each group. In our example, a steep stepped line (orange for mHP) indicates less variability, while a flatter stepped line (blue for mPWA) suggests more variability in performance.

Figure 1. An example of an ECDF graph.

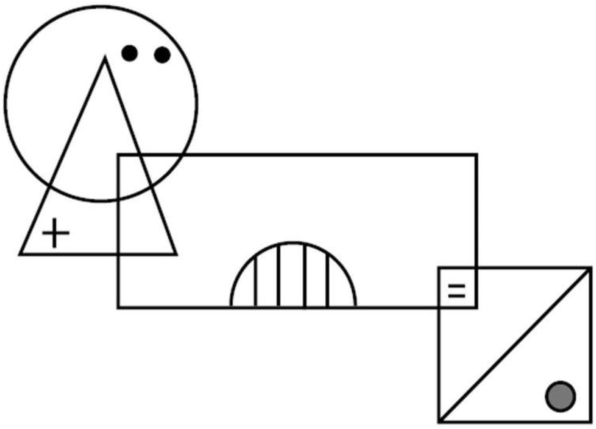


2.4. Assessment tools

The Rey-Osterrieth Complex Figure B Test (ROCF-B) is a valuable tool for assessing cognitive impairment, especially in individuals with aphasia (Lezak et al., 2012). The test assesses a range of cognitive functions, including visuospatial skills, visual memory, and executive functions, by requiring participants to copy and recall a complex geometric figure. The copying phase primarily assesses visuospatial skills, perceptual organization, and motor planning. After a three-minute delay, the participants were required to draw the figure from memory. This recalling phase assessed visual memory, organizational strategies, planning, monitoring, and inhibitory control (Kirkwood et al., 2001). Figure 2 illustrates the drawing included in the ROCF-B test. The maximum achievable score was 31. The scoring instructions included the following:

- The number of drawn elements (11 points): a circle, two small points, a triangle, a cross, a rectangle, an arc, a square, a diagonal line, an equal sign, a large point, four lines.
- The position of elements (8 points): a cross in the triangle, two points in the circle, a large point in the square, an arc in the rectangle, four lines inside the arc, the square, the equal sign, the diagonal line in the square.
- Overlaps (8 points): circle-triangle, triangle-rectangle, circle-rectangle, rectangle-square.
- The proportions between the four principal elements (4 points).

Figure 2. The Rey-Osterrieth Complex Figure B Test

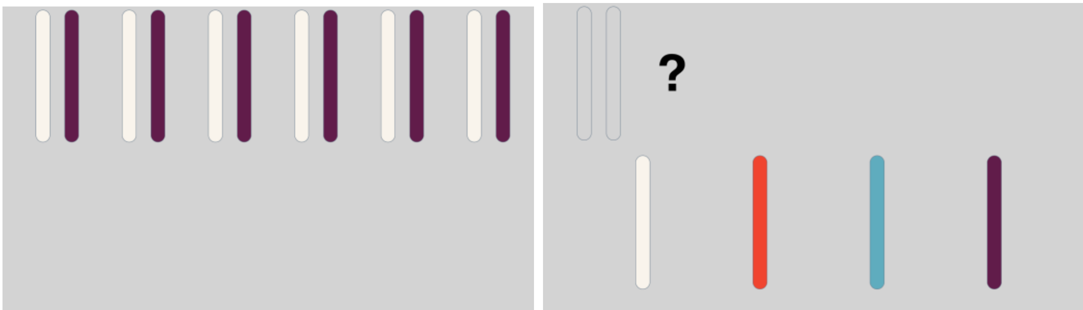


In the Auditory Sequential Memory Test, the participants were required to match words to corresponding pictures (see Figure 3). A trial test was conducted to determine if the participants understood and could carry out the task. If successful, a sequence of unrelated words was read aloud, and the participants were asked to reproduce the sequence by pointing to the corresponding pictures. The test began with a sequence of two words, which gradually increased to a maximum of nine. The maximum score achievable was 44. The images were sourced from a Hungarian Aphasia Therapy Exercise Book (Szabó & Sándor, 2021). The task measured working memory as well as cognitive flexibility and inhibition.

Figure 3. Pictures included in the Auditory Sequential Memory Test

A Visual Sequential Memory Test was applied from a Hungarian rehabilitation software which was made specifically for post-stroke patients (called Afázia App created by Katalin Nádudvari and Ali Baharev, PhD, available online at https://afazia.app/), involving coloured sticks and requiring the participants to memorise the order of 12 such sticks (Cseh & Hegyi, 1995, pp. 7-27). Each part of the test involved two colours, such as white and purple, but these had to be chosen from four different colours, namely white, red, blue, and purple (refer to Figure 4). The software instantly provided feedback to the participant, indicating whether the selected colour was correct or incorrect. All participants completed the test on the same tablet to ensure a consistent assessment environment. Their response times were measured in seconds to investigate the differences in performance between individuals with aphasia and those without. The test evaluated visual working memory and cognitive flexibility.

Figure 4. An example of the Visual Sequential Memory Test



3. Results

This section presents the results of the study investigating working memory impairments in participants with aphasia, specifically focusing on both the visual and verbal domains. The analysis involved two groups of aphasics: bilingual people with aphasia (bPWA) and monolingual people with aphasia (mPWA), as well as two reference groups: healthy bilingual participants (bHP) and healthy monolingual participants (mHP). The results are organised according to the three tests employed: the Visual Sequential Memory Test (VSMT), the Rey-Osterrieth Complex Figure B Test (ROCF-B), and the Auditory Sequential Memory Test (ASMT). The results are discussed in terms of response times (RT), percentages of mistakes, and overall performance scores, highlighting the implications of cognitive load for bilingual individuals compared to their monolingual counterparts. The individual scores of the bilingual and monolingual groups are displayed in Tables 6 and 7. As illustrated in Table 8, the results of the statistical analysis are presented alongside their respective p-values (*significant with Italic*).

Table 6. Results of the auditory and visual working memory tasks in the group of bilingual aphasics and the bilingual reference group.

Participants		Visual sequential memory test (mean RT in sec.)	Visual sequential memory (mistakes pct.)	ROCF-B (max score 31)	Auditory sequential memory test (max score 44)
Group of bilingual aphasics (N=8)	bPWA1	3.56	9.09	26	35
	bPWA2	1.34	2.70	30	36
	bPWA3	1.69	5.88	12	18
	bPWA4	2.19	7.69	27	44
	bPWA5	1.18	0	30	43
	bPWA6	3.55	22.58	0	0
	bPWA7	1.36	0	27	35
	bPWA8	5.74	40.00	0	3
Range of scores (min-max)		1.18-5.74	0-40	0-30	0-44
Mean score		2.58	10.99	19	26.75
SD		1.60	13.77	13.04	17.48
Bilingual reference group (N=18)	bHP1	1.19	0	21	42
	bHP2	1.11	2.04	31	44
	bHP3	1.24	0	21	44
	bHP4	1.12	0	31	44
	bHP5	1.28	4.00	26	35
	bHP6	1.44	2.04	31	42
	bHP7	1.55	5.88	15	29
	bHP8	1.19	4.00	31	35
	bHP9	2.03	4.00	26	36
	bHP10	1.38	7.69	25	38
	bHP11	1.8	0	27	34
	bHP12	1.49	4.00	23	42
	bHP13	1.02	0	31	44
	bHP14	2.04	0	22	35
	bHP15	1.06	0	26	42
	bHP16	1.17	0	24	42
	bHP17	1.07	0	29	44
	bHP18	1.01	0	26	40
Range of scores (min-max)		1.01-2.04	0-7.69	15-31	29-44
Mean score		1.34	1.87	25.89	39.56
SD		0.33	2.46	4.44	4.53

Table 7. Results of the auditory and visual working memory tasks in the group of monolingual aphasics and the monolingual reference group.

Participants		Visual sequential memory test (mean RT in sec.)	Visual sequential memory test (mistakes pct.)	ROCF-B (max score 31)	Auditory sequential memory test (max score 44)
Group of monolingual aphasics (N=10)	mPWA1	2.11	7.69	22	42
	mPWA2	3.2	7.69	11	30
	mPWA3	1.94	0	24	42
	mPWA4	4.85	45.45	13	23
	mPWA5	1.37	0	31	43
	mPWA6	1.21	4.35	24	20
	mPWA7	5.22	20.00	21	16
	mPWA8	3.09	14.29	17	26
	mPWA9	1.20	0	29	44
	mPWA10	2.49	11.11	7	14
Range of scores (min-max)		1.20-5.22	0-45.45	7-31	14-44
Mean score		2.67	11.06	19.90	30
SD		1.44	13.77	7.80	11.88
Monolingual reference group (N=18)	mHP1	1.27	0	31	44
	mHP2	1.05	0	30	44
	mHP3	1.21	0	15	44
	mHP4	2.27	4.00	30	37
	mHP5	1.23	2.04	31	44
	mHP6	1.31	0	28	39
	mHP7	1.15	0	24	40
	mHP8	2.04	6.25	22	30
	mHP9	1.47	0	31	44
	mHP10	1.16	0	29	44
	mHP11	1.82	17.24	23	42
	mHP12	2.05	5.26	22	41
	mHP13	1.04	0	27	44
	mHP14	1.28	5.26	25	40
	mHP15	2.56	7.69	31	42
	mHP16	1.88	14.29	15	26
	mHP17	0.99	0	31	42
	mHP18	1.43	0	24	40
Range of scores (min-max)		0.99-2.56	0-17.24	15-31	26-44
Mean score		1.51	3.45	26.06	40.39
SD		0.48	5.21	5.22	5.02

3.1. Results of the Visual Sequential Memory Test

3.1.1. Monolingual aphasics vs. bilingual aphasics

Results from the Visual Sequential Memory Test, administered to the bilingual aphasic participants, indicated a mean response time (RT) of 2.58 seconds (sec), with a standard deviation (SD) of 1.60. The average percent of mistakes made by this group was 10.99%, with an SD of 13.77. The range of errors varied from 0 to 40%, indicating a high degree of variance in performance among the participants. Individual levels of performance varied considerably; for instance, bPWA8 recorded the highest mean RT of 5.74 sec, and 40 % of the answers were wrong, while bPWA5 demonstrated the most efficient level of performance with a mean RT of 1.18 sec and no mistakes. This suggests that increased response times may correlate with a higher incidence of errors within the aphasia group.

In contrast, the mean RT of the monolingual aphasia group was 2.67 sec (SD = 1.44) in the VSMT, with an average percentage of mistakes made of 11.06% (SD = 13.77). The response times ranged from 1.20 to 5.22 seconds, exhibiting lower variability in performance compared to the bilingual aphasia group. The percentage of mistakes made for the monolingual aphasia group varied from 0 to 45.45%, once again highlighting the variability of performance. For example, the RTs and percentages of mistakes made for mPWA4 and mPWA7 were high, while the RTs for mPWA3 and mPWA9 were low, with no mistakes made. This suggests that, similar to the bilingual aphasia group, there may be a correlation between increased response times and the number of errors made.

In conclusion, although the mean RT for the bilingual aphasia group was lower than that for the monolingual aphasia group, the differences revealed a trend that did not reach statistical significance, and the same was valid for the percentage of mistakes. In both groups, participants with more severe aphasia symptoms demonstrated poorer performance than those with moderate or mild aphasia symptoms. As we hypothesised, the response time increased, and the number of mistakes rose, showing a positive correlation between response time and percentage of errors made for both aphasia groups.

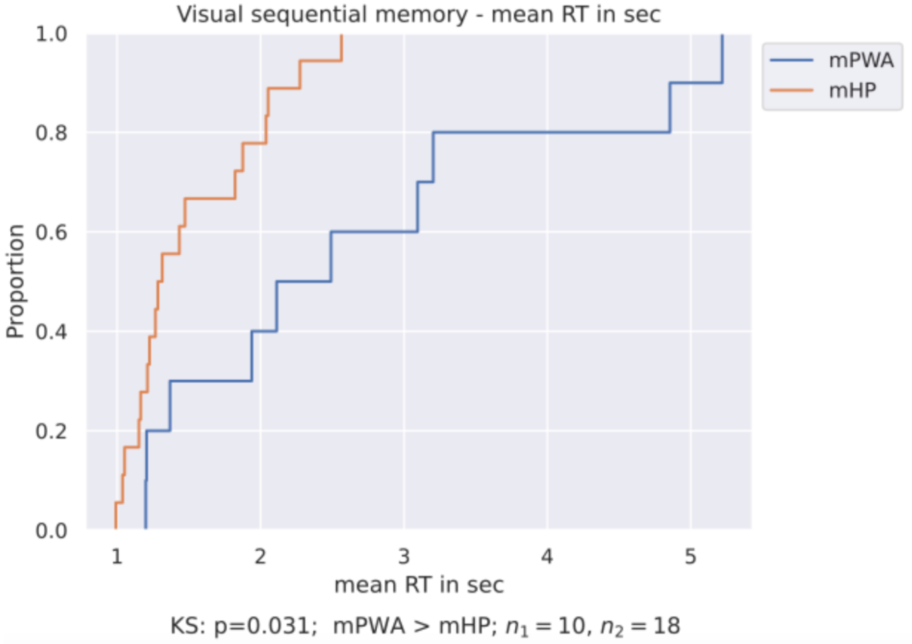
Table 8. Results from the statistical analysis of auditory and visual working memory tasks.

	Auditory sequential memory	ROCF-B	Visual sequential memory	
	number of correct answers	score	mean RT in sec.	mistakes pct.
mPWA (N=10) vs. bPWA (N=8)	p=0.514	p=0.148	p=0.623	p=0.737
mPWA (N=10) vs. mHP(N=18)	*p= 0.031* *aphasia < reference*	p=0.084	*p=0.031* *aphasia > reference*	p=0.066
bPWA(N= 8) vs. bHP (N=18)	p > 0.10	p > 0.10	*p=0.044 aphasia > reference*	*p=0.036 aphasia > reference*

3.1.2. Monolingual aphasics vs. monolingual reference group

The mean response time (RT) for the Visual Sequential Memory Test was significantly longer in the monolingual aphasia group in comparison with the monolingual reference group (refer to Figure 5). While the monolingual aphasia group exhibited a mean RT of 2.67 sec (SD = 1.44), the monolingual reference group performed the task with a mean RT of 1.51 sec (SD = 0.48). This difference indicates a notable impairment in visual sequential memory among individuals with aphasia. The range of RT scores for the monolingual aphasia group spanned from 1.20 to 5.22 sec, whereas the reference group's RT scores ranged from 0.99 to 2.56 sec. Additionally, we also assessed the percentage of mistakes made during the Visual Sequential Memory Test. The mean percentage of mistakes for the monolingual aphasia group was 11.06% (SD = 13.77), and for the reference group was 3.45% (SD = 5.21), without a statistically significant difference.

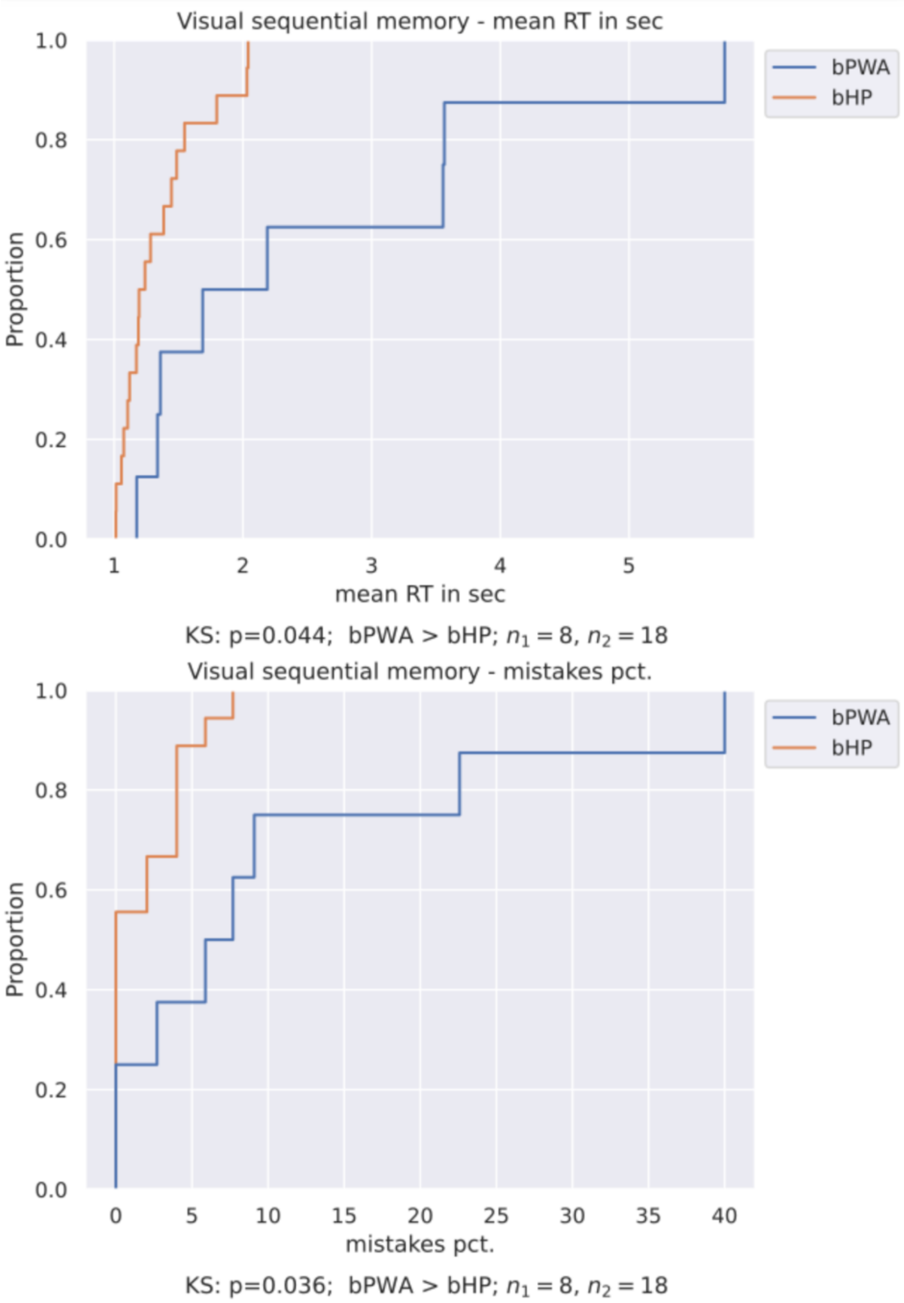
Figure 5. Comparison of the results from the Visual Sequential Memory Test recorded by the monolingual aphasics (mPWA) and monolingual reference group (mHP).



3.1.3. Bilingual aphasics vs. bilingual reference group

The response time (RT) results of the Visual Sequential Memory Test indicated a considerable degree of variability within the bilingual aphasia group. The mean RT for this group was 2.58 seconds (SD = 1.60), with a range from 1.18 to 5.74 seconds. In contrast, the bilingual reference group (N=18) demonstrated a significantly lower mean RT of 1.34 seconds (SD = 0.33) with scores ranging from 1.01 to 2.04 seconds. In addition, the bilingual aphasia group had a mean error rate of 10.99% (SD = 13.77) with a range of 0% to 40%. Conversely, the bilingual reference group exhibited a mean error rate of only 1.87% (SD = 2.46), with scores ranging from 0 to 7.69%. The higher error rates in the bilingual aphasia group suggest a well-expressed impairment of the visual working memory and reveal a double deficit in terms of response time and accuracy. This finding aligns with our first hypothesis that participants with aphasia underperform in visual memory tasks. As shown in Figure 6, a statistically significant difference was found between the two groups in both response time and the percentage of mistakes.

Figure 6. Comparison of the results from the Visual Sequential Memory Test recorded by the bilingual aphasics (bPWA) and the bilingual reference group (bHP).



3.2. Results from the Rey Complex Figure-B

3.2.1. Monolingual aphasics vs. bilingual aphasics

The results of the ROCF-B further elucidated the differences in cognitive processes assumed and observed in the tasks described above. The performance of the bilingual aphasia group in the ROCF-B test yielded a mean score of 19 (SD = 13.04), with scores ranging from 0 to 30, indicating a moderate level of impairment in visual memory as assessed by this test. While bPWA1 achieved a score of 26, bPWA6 and bPWA8, with more severe aphasia symptoms, scored the lowest, that is, 0. The monolingual aphasia group produced a mean score of 19.90

(SD = 7.80) in the ROCF-B, with scores ranging from 7 to 31. The bilingual individuals with aphasia scored lower on average than their monolingual aphasic counterparts, with no statistical difference.

3.2.2. Monolingual aphasics vs. monolingual reference group

The monolingual aphasia group had a mean score of 19.90 (SD = 7.80) out of a maximum score of 31, while the monolingual reference group achieved a mean score of 26.06 (SD = 5.22). This difference in mean scores suggests that individuals with aphasia demonstrate deficits in visual working memory compared to their healthy counterparts, although this trend is only apparent.

3.2.3. Bilingual aphasics vs. bilingual reference group

The bilingual aphasia group achieved a mean score of 19 (SD = 13.04), with scores ranging from 0 to 30. In contrast, the bilingual reference group had a mean score of 25.89 (SD = 4.44), with scores ranging from 15 to 31. Within the bilingual aphasia group, those exhibiting more severe aphasia symptoms demonstrated poorer performance compared to their counterparts (see Table 6 for individual scores). However, no statistical significance was found between the two groups.

3.3. Results from the Auditory Sequential Memory Test

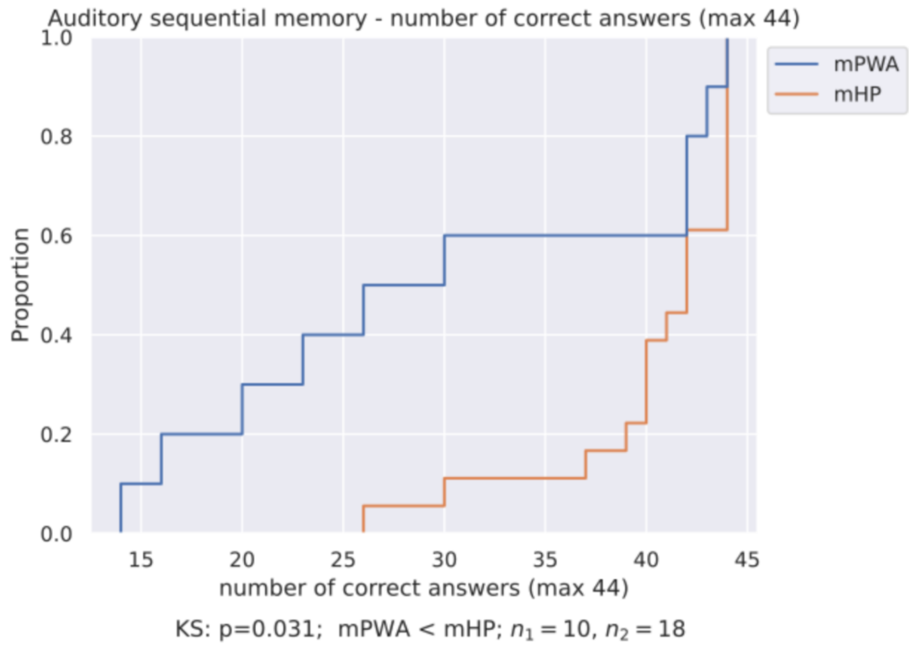
3.3.1. Monolingual aphasics vs. bilingual aphasics

The results from the Auditory Sequential Memory Test produced a mean score of 26.75 (SD = 17.48) for the bilingual aphasic participants, with scores ranging from 0 to 44, indicating a substantial level of impairment in verbal working memory. The monolingual aphasic participants achieved a mean score of 30 (SD = 11.88) in the ASMT, with scores ranging from 14 to 44. The analysis revealed that the monolingual aphasia group performed better than the bilingual aphasia group in the Verbal Working Memory Test, a trend that was not statistically significant.

3.3.2. Monolingual aphasics vs. monolingual reference group

The Auditory Sequential Memory Test results also revealed significant differences between the monolingual aphasia and reference groups (see Figure 7). The monolingual aphasia group exhibited a mean score of 30 (SD = 11.88) out of a maximum score of 44, while the reference group produced a mean score of 40.39 (SD = 5.02). This difference suggests that individuals with aphasia also experience impairments in auditory sequential memory. The scores recorded by the monolingual aphasia group ranged from 14 to 44, demonstrating variability in performance, with some individuals achieving scores close to the maximum, while others scored considerably lower. In contrast, the scores from the monolingual reference group ranged from 26 to 44, indicating the consistently better level of performance of these participants.

Figure 7. Comparison of the results from the Auditory Sequential Memory Test between the monolingual aphasics (mPWA) and the monolingual reference group (mHP).



3.3.3. Bilingual aphasics vs. bilingual reference group

To assess verbal working memory, we employed the Auditory Sequential Memory Test. The bilingual aphasia group had a mean score of 26.75 (SD = 17.48), with scores ranging from 0 to 44. In comparison, the bilingual reference group achieved a higher mean score of 39.56 (SD = 4.53), with scores ranging from 29 to 44. The findings suggest a potential deficit in auditory working memory among bilingual individuals with aphasia, although this is only a trend.

4. Discussion

The present study aimed to investigate working memory impairments in individuals with aphasia, with a specific focus on differences between bilingual and monolingual individuals with aphasia by using tests for the visual and auditory domains. The findings from the Visual Sequential Memory Test, the Rey Complex Figure Test, and the Auditory Sequential Memory Test provided critical insights into the cognitive load and performance discrepancies experienced by these aphasia groups.

Statistical analyses of results found in the investigated monolingual and bilingual aphasia groups did not reveal any significant differences, neither in the visual nor in the auditory working memory tests. The results of the Visual Sequential Memory Test confirmed significant performance variability in both the mono-and bilingual aphasia groups, as indicated by the wide range of response times and error rates. The mean response time difference between the two aphasia groups showed trends only and not statistical significance, suggesting similarities in cognitive load when engaged in visual memory tasks. The variability in performance observed in the aphasia groups, including participants who demonstrated markedly higher response times and error rates, indicates that individual differences might play a crucial role in the cognitive performance of these patients. Both the mono- and bilingual aphasia groups demonstrated impairments in visual memory as shown by the Rey Complex Figure B (ROCF-B) test. Again, the bilingual aphasia group achieved lower mean scores than the monolingual aphasia group, although the difference was not statistically significant. The variability in scores observed within the bilingual aphasia group, particularly among those with more severe aphasia symptoms, highlights the need for tailored interventions that focus on the clinical aspects of individual differences. Moreover, the Auditory Sequential Memory Test revealed a substantial level of impairment in verbal working memory both in the mono- and bilingual aphasia groups, with bilinguals scoring lower than monolinguals. Again, a trend is evident, but it lacks statistical significance. As expected, the aphasia and reference groups showed statistically significant differences both in the visual and auditory working memory tests.

Our finding of a significant impairment in visual sequential memory among individuals with aphasia is consistent with the existing literature, which highlights the complexity of cognitive deficits associated with aphasia, particularly in memory tasks (Mooijman et al., 2022). However, there were several tasks, such as the ROCF-B test, where the performance difference between aphasics and healthy participants showed trends similar to those in the Rey Complex Figure B test, but without statistical significance. Therefore, a logical question is whether these weaknesses add up in complex tasks and how they contribute to performance dissociations.

The results from the Auditory Sequential Memory Test (ASMT) further emphasise the role of auditory working memory deficits in language performance experienced by individuals with aphasia. The significant differences in mean scores on the ASMT between the aphasia groups and the reference groups highlight the impact of aphasia on cognitive functions, particularly in tasks requiring the retention and manipulation of verbal information. These results are in agreement with available literature on aphasia, drawing attention to the importance of highlighting the main difficulties of aphasic patients in auditory memory tasks.

The overall results of this study have significant clinical implications for the proper diagnosis, cognitive assessment, therapy, and treatment of working memory impairments in individuals with aphasia. Given the observed deficits in both visual and auditory working memory, clinicians should consider introducing targeted memory training exercises in rehabilitation programmes. These interventions should be tailored to address the specific challenges faced by bilingual individuals with aphasia, taking into account the cognitive load associated with managing multiple languages. Moreover, the variability in performance within the bilingual aphasia group underscores the importance of individualised assessment and intervention strategies. Clinicians should be aware of the potential for significant differences in cognitive processing among bilingual individuals with aphasia, and assessments should be designed to capture these individual differences accurately. Individuals with aphasia could be better supported if personalised, fit-for-purpose approaches were introduced to overcome the specific cognitive challenges.

5. Conclusion

In conclusion, the findings of this study underscore the intricate relationship between bilingualism, aphasia, and working memory. Both bilingual and monolingual individuals with aphasia demonstrated impairments in the visual and auditory working memory. These results underscore the importance of considering individual differences in cognitive processing when assessing and treating individuals with aphasia. By adopting a comprehensive approach that takes into account the unique challenges faced by bilingual individuals, clinicians can improve therapeutic outcomes and support individuals in their recovery. Further research is needed to explore the intricacies of working memory in bilingual populations affected by aphasia, ultimately contributing to a more comprehensive understanding of cognitive functions in this context.

6. Limitations

While this study provides valuable insights into working memory impairments in bilingual and monolingual individuals with aphasia, the results, along with further assumptions and suggestions, are not without limitations. One reason is the relatively small sample size, which limits the generalizability and broader applicability of the findings. Additionally, the lack of statistically significant differences between the mono-and bilingual aphasia groups reflects the need for further research with larger samples to explore these trends more comprehensively. Future studies should consider longitudinal designs to assess changes in working memory performance over time, particularly in response to targeted interventions. Furthermore, research exploring the neural correlates of working memory in bilingual individuals with aphasia may provide deeper insights into the cognitive processes involved. A proper design of behavioural tasks may be supported by a better understanding of the underlying mechanisms in individuals with aphasia, which contributes to developing more effective therapeutic approaches that cater to the unique and special needs of bilingual individuals with aphasia.

References

Adrover-Roig, D., Galparsoro-Izagirre, N., Marcotte, K., Ferré, P., Wilson, M. A., & Inés Ansaldo, A. (2011). Impaired L1 and executive control after left basal ganglia damage in a bilingual Basque–Spanish person with aphasia. *Clinical Linguistics & Phonetics*, *25*(6–7), 480–498. doi: https://doi.org/10.3109/02699206.2011.563338

Baddeley, A. (2003). Working memory: Looking back and looking forward. *Nature Reviews Neuroscience, 4*(10), 829–839. https://doi.org/10.1038/nrn1201.

Chapey, R. (2008). Language Intervention Strategies in Aphasia and Related Neurogenic Communication Disorders, Chapter 33, 879-962. Baltimore, MD: Lippincott Williams & Wilkins.

Christensen, S. C., & Wright, H. H. (2010). Verbal and non-verbal working memory in aphasia: What three *n*-back tasks reveal. *Aphasiology*, *24*(6–8), 752–762. https://doi.org/10.1080/02687030903437690

Christensen, S. C., Wright, H. H., & Ratiu, I. (2018). Working memory in aphasia: Peeling the onion. *Journal of Neurolinguistics*, *48*, 117–132. doi: https://doi.org/10.1016/j.jneuroling.2018.02.001

Cseh, K., & Hegyi., Á. (1995). *Gyakorlatok az afázia kognitív nyelvi terápiájához*. Budapest, Hungary: Nemzeti Tankönyvkiadó.

Dodge, Y. (2008). Kolmogorov-Smirnov Test in *The Concise Encyclopedia of Statistics*. Springer , New York, NY doi*:* https://doi.org/10.1007/978-0-387-32833-1_214

Gitterman, M. R., Goral, M., & Obler, L. K. (Eds.) (2012). *Aspects of Multilingual Aphasia. Bristol, Buffalo*, Toronto: Multilingual Matters. ISBN-13: 978-1-84769-754-7

Goetz, C. G. (2007). Textbook of Clinical Neurology (3rd Ed.). Philadelphia, PA: Saunders. ISBN 978-1-4160-3318-0.

Kirkwood, M.W., Weiler, M. D., Bernstein, J. H., Forbes, P. W., & Waber, D. P. (2001). Sources of Poor Performance on the Rey- Osterrieth Complex Figure Test among children with learning difficulties: a dynamic assessment approach. *The Clinical Neuropsychologist, 15(3),* 345-56. doi: https://doi.org/10.1076/clin.15.3.345.10268

Lee, B., Moon, H. I., Lim, S. H., Cho, H., Choi, H., & Pyun, S.-B. (2016). Recovery of language function in Korean-Japanese crossed bilingual aphasia following right basal ganglia hemorrhage. *Neurocase*, *22*(3), 300–305. doi: https://doi.org/10.1080/13554794.2016.1141966

Lezak, M. D., Howieson, D. B., Bigler, E. D., & Tranel, D. (2012). Neuropsychological Assessment (5th ed.). Oxford University Press.

Mayer, J. F., & Murray, L. L. (2012). Measuring working memory deficits in aphasia. *Journal of Communication Disorders*, *45*(5), 325–339. doi: https://doi.org/10.1016/j.jcomdis.2012.06.002

Mooijman, S., Schoonen, R., Roelofs, A., & Ruiter, M. B. (2022). Executive control in bilingual aphasia: A systematic review. *Bilingualism: Language and Cognition*, *25*(1), 13–28. doi: https://doi.org/10.1017/s136672892100047x

Murray, L.L., Ramage, A. E., & Hopper, A. (2001). Memory impairments in adults with neurogenic communication disorders. *Seminars in Speech and Language, 22 (2), 129-136*. doi: https://doi.org/10.1055/s-2001-13937

Nikravesh, M., Aghajanzadeh, M., Maroufizadeh, S., Saffarian, A., & Jafari, Z. (2021). Working memory training in post-stroke aphasia: Near and far transfer effects. *Journal of communication disorders*, *89*, 106077. doi: https://doi.org/10.1016/j.jcomdis.2020.106077

Noether, G. E. (1963). Note on the Kolmogorov statistic in the discrete case. *Metrika*, *7*(1), 115–116. doi: https://doi.org/10.1007/bf02613966

Penn, C., Frankel, T., Watermeyer, J., & Russell, N. (2009). Executive function and conversational strategies in bilingual aphasia. *Aphasiology*, *24*(2), 288–308. doi: https://doi.org/10.1080/02687030902958399

Penn, C., Barber, N., & Fridjhon, P. (2017). Early recovery profiles of language and executive functions after left hemisphere stroke in bilingualism. *Aphasiology*, *31*(7), 741–764. doi: https://doi.org/10.1080/02687038.2016.1258538

Potagas, C., Kasselimis, D., & Evdokimidis, I. (2011). Short-term and working memory impairments in aphasia. *Neuropsychologia*, *49*(10), 2874–2878. doi: https://doi.org/10.1016/j.neuropsychologia.2011.06.013

Slakter, M. J. (1965). A Comparison of the Pearson Chi-Square and Kolmogorov Goodness-of-Fit Tests with Respect to Validity. *Journal of the American Statistical Association*, *60*(311), 854–858. doi: https://doi.org/10.1080/01621459.1965.10480833

Szabó E., & Sándor, K. (2021). *Afáziás feladatgyűjtemény I.* ISBN 978-615-81597-8-4 Retrieved from: https://www.efiportal.hu/wp-content/uploads/2021/07/afaziaterapias-feladatgyujtemeny-i_.pdf

Virtanen, P., Gommers, R., Oliphant, T.E. *et al.* (2020). SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature methods*, *17*(3), 261–272.doi: https://doi.org/10.1038/s41592-019-0686-2

Walsh, J. E. (1963). Bounded probability properties of Kolmogorov-Smirnov and similar statistics for discrete data. *Annals of the Institute of Statistical Mathematics*, *15*(1), 153–158. doi: https://doi.org/10.1007/bf02865912

Wright, H. H, & Shisler, R.J. (2005). Working memory and aphasia: theory, measures, and clinical implications. *American Journal of Speech-Language Pathology, 14 (2), 107-118*. doi: https://doi.org/10.1044/1058-0360(2005/012) .

Zakariás, L., Salis, C., & Wartenburger, I. (2018). Transfer effects on spoken sentence comprehension and functional communication after working memory training in stroke aphasia. *Journal of Neurolinguistics, 48,* 47-63. doi: https://doi.org/10.1016/j.jneuroling.2017.12.002