Exercise and Language Performance in Healthy Aging, Stroke and Neurodegenerative Conditions: a Scoping Review

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ABSTRACT

Background

While the benefits of exercise on cognitive functions have already been reviewed, little is known about the impact of exercise on language performance. This scoping review was conducted to identify existing evidence on exercise-induced changes in language performance in healthy aging individuals and adults with stroke or neurodegenerative conditions.

Methods & Results

Using the Arksey and O'Malley framework, 29 studies were included. Eleven studies in healthy aging indicated enhanced language performance, with 72.72% having significant improvement in semantic/phonological Verbal Fluency (VF) following exercise. Among 18 studies on older adults with stroke or neurodegenerative conditions, 11 reported better language performance, with 44.44% having significant improvement in picture naming/description and semantic/phonological VF by exercise. The seven remaining studies reported no significant change in language performance in persons with stroke or neurodegenerative conditions.

Conclusion

Overall, exercise interventions showed improvement in language performance in healthy aging, while selective enhancement was shown for language performance in persons with either stroke or neurodegenerative conditions.

Key words: language impairment, exercise interventions, healthy aging, neurodegenerative conditions

Introduction

The American College of Sports Medicine[1] defines exercise as a "type of physical activity consisting of planned, structured, and repetitive bodily movement done to improve and/or maintain one or more components of physical fitness".[2] In addition to the physiological benefits of exercise,[3] studies on the effect of exercise on several aspects of cognitive functions reported improvement in information processing, reaction time, attention in older adults,[4] and memory in young and older adults.[5] Some of these cognitive functions are mediated by frontal and prefrontal brain regions, which are also involved in different language functions.[6]

Language is subserved by adaptable language networks across several brain regions. Activation, coordination, and integration of complex functions of the linguistic system (e.g., the lexicon, semantics, morphology, and syntax) along with other cognitive functions/domains, such as memory, attention, speed processing, and inhibition, are operative during language performance.[7] Two common factors that can influence language performance are aging and neurological conditions. Aging triggers a set of physiological and neurobiological changes that produce cognitive changes leading to language alterations (e.g., difficulty in word retrieval). In addition, neurological conditions resulting in changes to frontal, temporal, or parietal cortices can affect language production and comprehension and attenuate verbal fluency or access to word features, (e.g., semantics, phonology, or syntax). This can result in disconnected barely meaningful speech, derailed stories, and inefficient yet extraneous conversations.

Verbal Fluency (VF) which is predominantly representative of language abilities,[8] refers to producing a series of words from a predefined category engaging frontal executive functions and working memory, strategic search, error control, and monitoring.[9] The two most common types of VF tasks are semantic, where participants are asked to generate words belonging to a specific semantic category such as "animals", and phonemic, where they are asked to generate words beginning with a specific letter or phoneme. Difficulty in retrieving and remembering words can affect relaying main ideas observed in picture description in healthy aging[10] and older adults with neurological conditions.[11]

Picture description refers to expressing information about a single picture or series of pictures, and is commonly employed for eliciting narrative discourse samples from both healthy and clinical populations.[10,11] Picture description involves various linguistic features (e.g., semantics, phonology), and cognitive functions (e.g., selective attention and memory). Word-finding difficulty during spontaneous speech, picture description, or storytelling is one of the most prevalent cognitive and linguistic changes in healthy aging and older adults with neurological conditions. Lack of proper communication and fluent speech might lead to ineffective communication, resulting in difficulties in receiving appropriate care or potential self-isolation. Given that exercise can induce selective enhancement in the frontal brain region,[4,12] and this region plays a prominent role in language performance,[6,9] it is important to investigate whether exercise can affect language performance. This can help identify feasible and cost-effective adjunct approaches to promote healthy cognitive aging, delay normal age-related cognitive difficulties, and develop more efficient treatments for neurological conditions.

The premise driving research on exercise is that this intervention triggers neurophysiological mechanisms such as the release of neurotransmitters such as dopamine and serotonin, or changes in blood oxygenation levels in brain regions involved in cognitive processing. Exercise also showed to increase gray matter volume specifically in the hippocampus and prefrontal regions involved in memory, executive functions, and language processing.[13] These structural changes suggest that exercise can enhance neuroplasticity;that is to say, the ability of the brain to reorganize and restructure, especially in the hippocampal and prefrontal areas. Enhanced neuroplasticity by exercise was reported to be associated with better cognitive functions.[14,15] Improved cognitive functions, in turn, can facilitate performance in language tasks.

The literature in support of the benefits of exercise on information processing, memory, and attention has already been reviewed[5,14] with little attention on language performance in healthy aging and older adults with stroke or neurodegenerative conditions. A recent review of cognitive and linguistic effects of aerobic exercise revealed potential positive results on language performance post-stroke.[16] However, the studies included in the Mayer *et al*.[16] review addressed only individuals with stroke and aphasia while the effect that exercise may have on language performance in healthy aging as well as in stroke and neurodegenerative conditions is yet to be summarized. This scoping review was conducted to identify and synthesize existing evidence on the effect of exercise on language performance in aging adults without or with stroke or neurodegenerative conditions.

METHODS

The scoping review methodology, as proposed by Arksey and O'Malley[17] and later advanced by Levac et al.,[18] was followed through five of the six binding stages outlined below. The last stage (Stage 6–Consulting with Experts), which is optional, was not conducted as one of the authors is an expert in language (E.K.). In what follows we describe the methodology and procedure.

Stage 1– Identifying the Research Question

The research question was: What is currently known about the effect of exercise on language performance in healthy aging and older adults with stroke or neurodegenerative conditions? We were also interested in identifying the language assessments used and the aspects of language performance targeted. This information can provide further insights on the effect of exercise on language performance highlighting more sensitive measures reflecting exercise-induced changes. We hypothesized that exercise can enhance performance on language tasks that place demands on linguistic processes and higher-level executive functions mediated by (pre)frontal brain regions like VF or naming tasks. Other language tasks involving more semantic processes, like picture description, may also benefit from exercise.

Stage 2–Identifying Relevant Studies

The authors who include an expert in neuro/psycholinguistics (E. K.), an expert in exercise science and sport medicine (M. R.), and their PhD student in Rehabilitation Science (R. K.), with the assistance of an expert medical librarian, selected 18 key search terms comprising variants of keywords for exercise and language. (For the keywords see Appendix A.)

Both Medical Subject Headings (MeSH) and keywords, including their relevant subcategories with truncation symbols and wild cards, were used for the search terms. A comprehensive search of the literature was performed on four databases OVID MEDLINE, PubMed, CINAHL, and Cochrane Library. A first search was performed in October 2018 and was repeated in April 2021 and in September 2022 by the first author (R. K) and a research assistant. In the first search, 207 studies were retrieved; the second search retrieved 252 studies; and the final search retrieved 283 studies. Additionally, the first author hand-searched the bibliographical references of the included studies to identify studies that might not emerge from the database search.

Stage 3–Study Selection

Studies were included if: 1) the full texts were published in English or French and had language performance as an outcome; 2) they were clinical trials, cross-sectional and single-case studies, as well as studies with a within-subject design, all exploring the effect of exercise interventions on language performance and/or cognitive function with at least one language component; 3) the studied populations were adults with mean age ≥45 years old with and without stroke or neurodegenerative conditions which can be accompanied by language limitations including stroke, Mild Cognitive Impairment (MCI), Alzheimer's disease (AD) and other dementias, as well as Parkinson's disease (PD). The specific age group was selected because most neurodegenerative conditions, such as AD and PD, have aging as their primary risk factor.[19] Also, the risk of incidence of stroke doubles after 45 years.[20] Neurological conditions, like multiple sclerosis, were not the focus of this paper as speech-motor deficits observed in such conditions are found to be heavily associated with a dysexecutive syndrome rather than a language deficit.[21]

Studies were also included if: 4) they used any type of exercise intervention such as cardiovascular and resistance exercise, with either well-defined exercise parameters (i.e., FITT= Frequency, Intensity, Time (duration) and Type), or evidence of significant exercise workload increases in volume and/or intensity; and 5) they used acute or chronic exercise protocols. Acute exercise refers to a single bout of exercise that is sufficient to induce a systemic physiological response, for example, an increase in heart rate and body temperature.[5,22] We defined chronic exercise as interventions lasting at least four weeks with training sessions performed at least twice per week.[23]

Studies were excluded if: 1) participants were children, adolescents, or young adults; 2) participants had developmental language disorders (e.g., primary language impairment, autism, and fragile X syndrome); 3) no evidence of significant workload increases in volume and/or intensity was provided; 4) exercise interventions required very low energy consumption and merely targeted balance, fall, or gait control that were not intense enough to induce a systematic physiological response and training adaptation; 5) exercise interventions were combined with other non-exercise interventions such as cognitive training, having potential confounding or facilitatory effects on language unless the effect of exercise alone could clearly be evaluated having a control condition; 6) published as non-experimental publications such as reviews; and 7) published as book chapters, dissertations, protocols, or conference posters. However, the reference lists of these documents were searched and relevant studies were considered.

The study selection process comprised three phases. First, the scientific references were imported into EndNote X9.3.3 (Clarivate, London) and duplicates were removed. Then, the list of the titles and abstracts of the 535 remaining articles was imported into the Rayyan platform (https://www.rayyan.ai/), and two reviewers (R. K. & E. K.) independently selected the eligible articles. 98.31% agreement was achieved for the full text (56 included, 470 excluded, and 9 conflicts). A third reviewer (M. R.) resolved the conflicts. Full texts of the final 56 studies were assessed for eligibility and 29 studies were finally selected based on the above-mentioned inclusion criteria. The study selection process is presented in the PRISMA flowchart (see Figure 1).

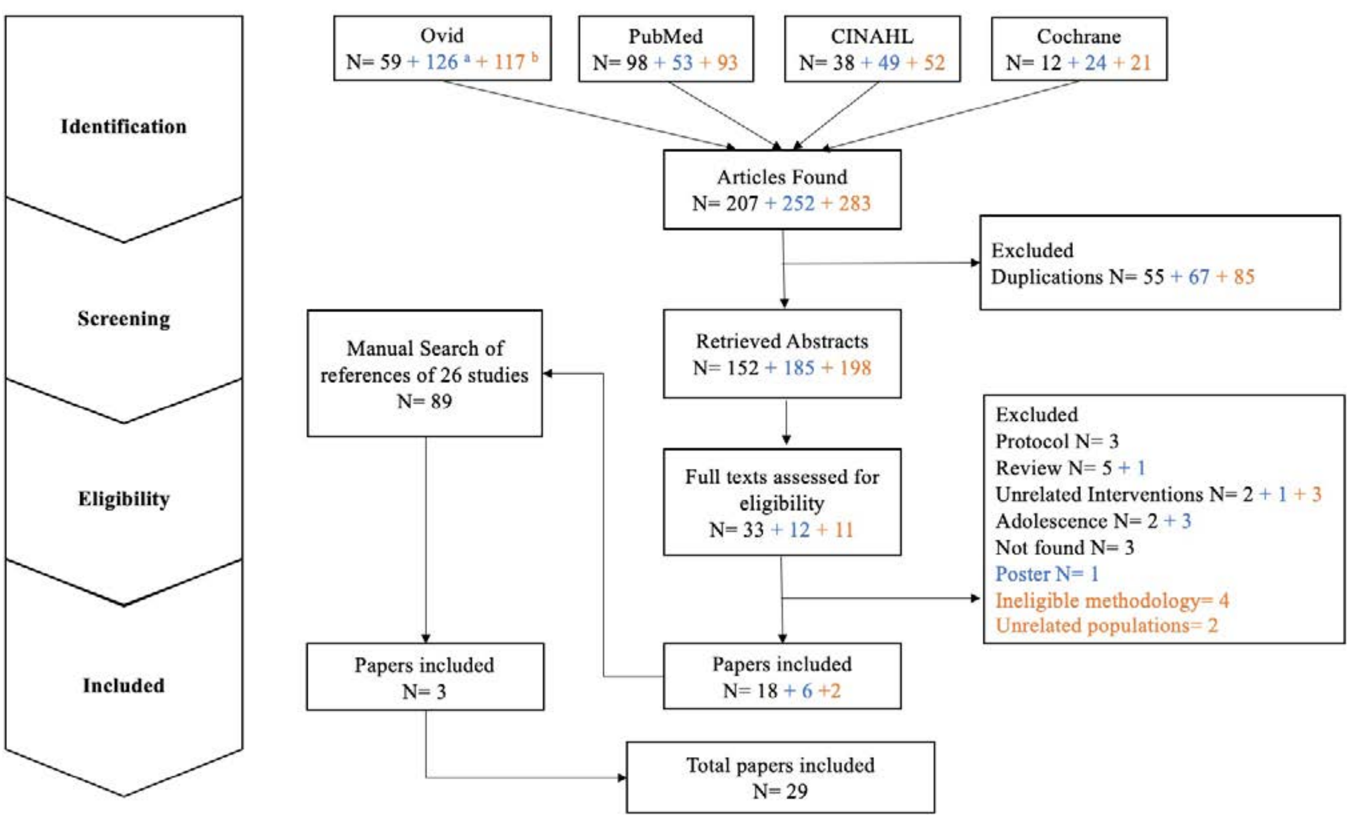

Figure 1. PRISMA flowchart of the study screening process
[a]The number of articles retrieved from the second search in 2021 was added in blue colour.
[b]The number of articles retrieved from the third search in 2022 was added in orange colour.

Stage 4–Extracting and Charting the Results

A data extraction sheet was created and included the title, year, place of publication, setting, abstract, purpose of the study/research question, study design, type, number, groups of participants, and the inclusion and exclusion criteria. It also included the studies' intervention and control conditions, baseline and outcome measures, assessment times, as well as strengths and limitations (see Appendix B).

The findings of the 29 included studies were tabulated and categorized using the International Classification of Functioning, Disability, and Health (ICF).[24] This framework was selected to ensure uniformity between reviewers when categorizing the outcomes into the most relevant themes. Furthermore, using ICF codes offered a broader range of structures and functions where change could occur (see Appendix C). After reaching a consensus regarding the ICF codes appropriate for each outcome, data from the 29 studies were independently reviewed and tabulated by two authors for each article. The three ICF domains scoped here were: Body Functions including Specific Mental Functions, Functions of Cardiovascular Hematological, Immunological and Respiratory Systems, and Neuromusculoskeletal and Movement-Related Functions; Body Structures including Structures of the Nervous System; and Activities and Participation including Learning and Applying Knowledge, and Mobility.

Given the complex nature of language, integrating both general cognitive and purely linguistic processes, outcome measures were categorized on a continuum that comprised two types of domain assessments: 1) Measures primarily assessing linguistic functions (e.g., VF or lexical decision) both targeting the access to the mental lexicon in different modalities (production and recognition); ICF code b167–Mental Functions of Language was used; and 2) Measures assessing global cognitive functions with at least one language component (e.g., Mini-Mental State Examination (MMSE),[25] or Montreal Cognitive Assessment (MoCA),[26] both tests targeting several linguistic domains (e.g. semantics, lexical access); ICF codes b164–Higher-level Cognitive Functions and b144–Memory Functions were used, while b167 was also integrated.

Stage 5–Collating, Summarizing, and Reporting the Results

The extraction tables were collated and all the ICF codes were validated by the first author. All three reviewers reached a consensus on the validation of the ICF codes. Analysis of the designated codes was performed after validation. A mapping of the ICF codes for the outcome measures was conducted using the D3 JavaScript library (https://d3js.org/) (see Figure 2). In Figure 2, the size of each circle depicts the frequency of codes attributed to the outcome measures. It

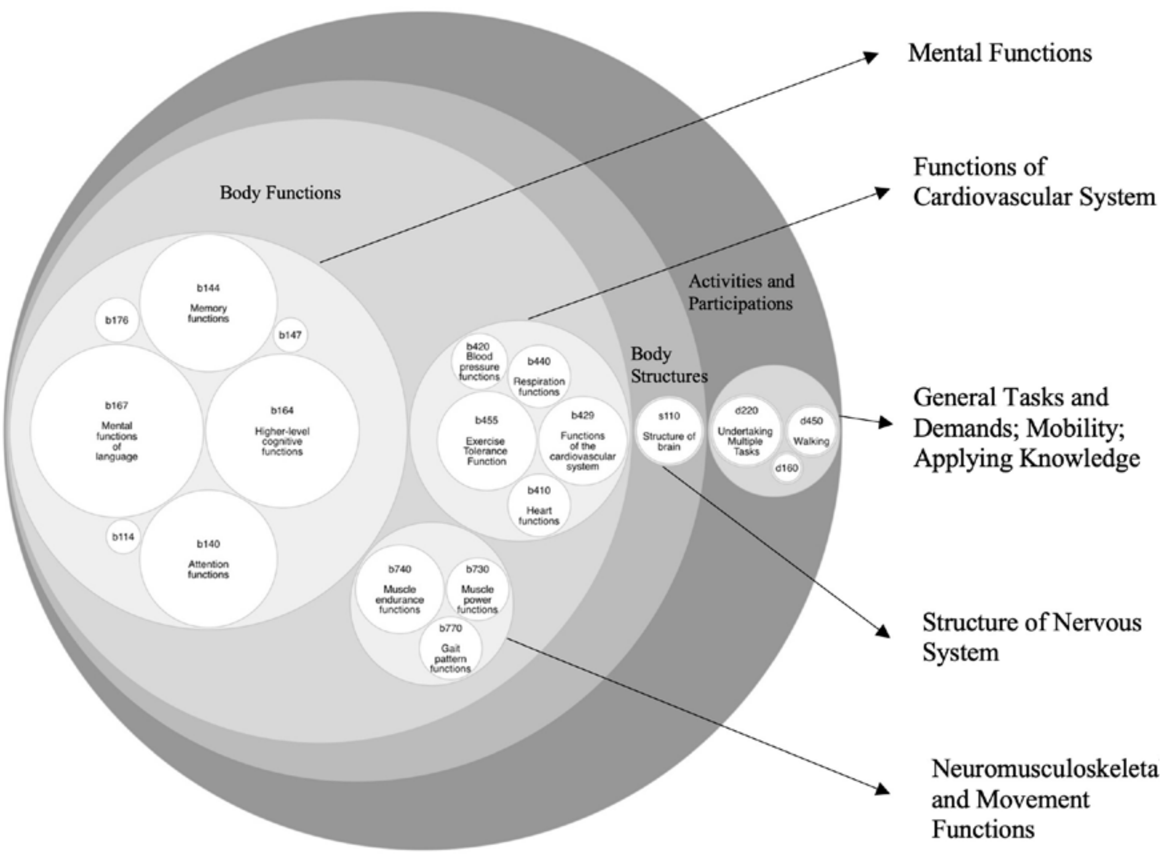

FIGURE 2. Mapping of ICF (2001) codes for the raw data
ICF Codes: b176–Mental function of sequencing complex movements; b147– Psychomotor functions; b114–Orientation functions; d160–Focusing attention.

is noteworthy to mention that to attribute the most specific code(s) to each outcome, we often used more than one code. For instance, we assigned b140–Attention Functions, b164–Higher Cognitive Functions, and b167–Mental Functions of Language to the Stroop task (see Appendix C).

RESULTS

The results are reported in the flowchart of the study selection (see Figure 1). Twenty-nine studies (21 studies from the first search in 2018, six and two studies from the second and third search in 2021 and 2022, respectively) met the inclusion criteria. In the following sections, we first describe the characteristics of the included studies and then the main findings.

Descriptive Summary of the Studies

The main characteristics of the included studies— design, population, intervention, outcome assessments, and findings—are briefly described in Table 1. Ten studies were carried out in the US, six in Brazil, four in Australia, two in Germany, and one each in Canada, the Netherlands, Sweden, Denmark, Finland, China, and Egypt, respectively. Most of the studies (62.06%, n=18) were Randomized Control Trials (RCTs),(12,27-43) nine within-subject,(44-52) one cross-sectional,(53) and a case study.(54) Among the included studies, 11 examined older adults without any neurological or neurodegenerative disease,(12,27,35,37-39,41,42,46,50,53) six assessed dementia and/or AD,(28,31,34,40,43,51) three PD,(45,47,54) two included individuals with stroke,(48,49) another five included individuals with MCI,(29,32,36,44,52) and two single studies on older adults with cognitive deterioration(30) and older adults with depression.(33) The mean age of the participants was above 65 in 22 studies, and between 48 and 65 in seven studies (see Table 1 for details).

Exercise interventions were chronic protocols, except for three studies in which acute protocols were implemented.(37,46,50) The exercise intensity was moderate to vigorous, varying between 40–85% Heart Rate Reserve (HRR) and 10–15 repetition maximum. One acute program applied 65% HRR;(50) one assessed the dose-response to 25-min cycling at 60%, 90%, and 110% anaerobic threshold;(46) and another compared 50–70% and 85–95% HRpeak.(37) Seventeen (62.96%) applied multimodal interventions consisting of either different exercise modalities or exercise adjunct to other therapies/training.(27,28,30-32,35,36,38,40,41,43,47-50,53,54) Eleven studies (37.03%) used one modality of exercise.(12,29,33,34,39,42,44-46,51,52) The duration of the intervention ranged from 20 to 90 min (mean ± SD: 48.67 ± 17.81), with a frequency from two to four days a week (3 ± 0.76) and spanned 6.5 to 48 weeks (15.66 ± 8.42).

Except for one case study,(54) all others had one control group maintaining normal activities or receiving usual health care. In some studies, control groups received multimodal training including resistance and stretching,(12,30) physiotherapy,(48) stretching exercises and language therapy,(53) stretching exercises,(29,37) aerobic exercises,(44,52) or cognitive training(38,41) at an equal frequency and duration as the intervention.

Main Findings

A summary of the language and cognitive outcomes of the studies is shown in Table 1. We found that 75.86% of the studies showed positive effects of exercise on language performance, but in only 65.51% of all studies this effect was statistically significant. An analysis of the positive effects of exercise on different language aspects showed enhanced semantic VF in 27.58% of the studies, and 17.24% reported improvement in both semantic and letter VF. Additionally, 13.79% of the studies reported positive effects in letter VF, and 17.24% of the studies reported better picture naming and description. In the following section, we review the intervention parameters and outcome measures. Then, we further discuss the effect of exercise on language performance and identify different language aspects—verbal fluency and picture naming—targeted in older adults.

Studies Involving Healthy Aging Adults

All 11 studies including healthy older adults, that is persons without stroke or neurodegenerative conditions (n= 676, 565 females), indicated improved language performance including semantic and letter VF following exercise interventions (see Table 1).

Outcome Measures

The detailed language and cognitive assessments used along with the ICF codes(24) assigned to each tool are presented in Appendix C. Semantic and letter VF were both assessed in five studies.(12,38,39,41,42) Two studies assessed only Semantic VF(35,46) and one study assessed only letter VF.(53) One study did not specify the type of VF used.(27) An associative novel word learning task(37) and naming via the Boston naming tests(35) were measured. The cognitive and language assessments used in these studies were Hopkins Verbal Learning Test,(12) Immediate and Delayed Recall, Verbal Memory, or Word List recall,(35,41) Stroop Word Interference Test,(35,38,42,50) Digit Span Forward & Backward,(12,38,42) and MoCA or MMSE.(27,35,42)

Studies Involving Adults with Stroke or Neurodegenerative Conditions

Among the 18 included studies involving older adults with stroke or neurodegenerative conditions (n= 1403, 816 females), 11 studies (61.11%) reported improved language performance including picture naming/description and semantic and letter VF induced by exercise.(29-32,34,44,45,47,49,52,54) Of these, eight (44.44%) found a statistically significant improvement in VF and picture description,(29,31,32,34,44,45,52,54) improved picture naming in stroke,(49) and picture description and semantic VF in PD.(45,47,54) Studies involving older adults with depression,(33) stroke,(48) AD and/or dementia reported no significant change in semantic VF.(28,36,43,52) while one study showed deteriorated semantic VF in older adults with AD.(40)

Outcome Measures

Semantic and letter VF were assessed in seven studies.(29,31,34,44,47,52,54) Six studies assessed only Semantic VF,(28,30,32,40,43,51) and one study assessed only letter VF.(36)

TABLE 1 (part 1 of 5).
Summary of the included studies

Study: Authors (Year) Country	*Design*	*Population[a] (Number, Groups, Age, Participants)*	*Intervention Frequency, Intensity, Time, Type (FITT)*	*Control*	*Language / Cognitive Assessments[b]*	*Summary of Main Findings*
Alfini *et al.* (2019)[44] USA	Within Subject	n= 32 G= 2 A= 78.4 ± 6.8 P= MCI & Healthy	F= 4 d/wk, for 12 wks I= Moderate- 50–60% HRR T= 30 min T= Treadmill walking	Healthy older adults received the same intervention.	VFT (S & L), COWAT; DRS-2 Logical Memory & Letter-Number Sequencing (WMS-III) RAVLT; verbal working memory & delayed-recall, MMSE, SDMT	Both groups showed significant improvement in global cognitive functions, memory, & VF.
Altmann *et al.* (2016)[45] USA	Within subject	n= 30 G= 3 (AE; Stretch-balance) A= 64.63 ± 8.5 P= Idiopathic PD	F= 3 d/wk for 16wks I= 50-75% of HRR T= 20-45min T= G1: AE: walking on a treadmill; G2: Stretch-balance tasks on a force platform with visual feedback displayed on a large computer monitor.	No-contact group. (Were doing regular daily activities & their physical activity levels were assessed by phone & questionnaires).	Picture description, Simple attention, 0-back, Stroop, DS F&B	AE group showed faster processing of dual tasks than single tasks & significant improvement in completing information in picture description than the stretch-balance group.
Ansai & Rebelatto (2015)[27] Brazil	RCT	n= 69 G= 3 A= 82.4 ± 2.4 P= ND- Sedentary	F= 3d/wk (non-consecutive days) for 16 wks I= 60-85% HRR T= 60 min T=Multicomponent (MT): aerobic, strength, & balance & resistance (RT)	No contact (CO)	VFT, MoCA, CDT, Dual task: TUGT with repeating weekdays in reverse order	RT showed significantly better global cognitive functions, naming, and attention compared to MT. MT showed worse performance on attention and naming domains of MoCA than MT and CO. MT showed a lower number of correct words per time compared to CO.
Arcoverde *et al.* (2014)[28] Brazil	RCT	n= 20 G= 2 A= 78.5 (64- 81.2) P= AD & mixed D	F= 2d/wk for 12 Wks I= 40-60% Vo2max T= 30min T=Multicomponent: Treadmill walking & stretching	Attended the hospital to maintain the clinical & pharmacological treatment.	VFT (S) Cambridge Cognitive Examination CDT; RAVLT; DS F&B, TMT A; Stroop	Exercise group showed improved general cognitive functions with maintained VF while the control group showed worsening cognitive functions.
Baker *et al.* (2010)[29] USA	RCT	n= 20 G= 2 A= 70 ± 8.32 P= MCI	F= 4d/wk for 24 wks I= 75– 85% HRR T= 45-60min T= AE (Cycling, treadmill, elliptical trainer)	Stretching Exercise while maintaining HR at or below 50% HRR	VFT (S & L) TMT B; Stroop, Story Recall; Delayed-Match-To-Sample	AE groups compared to the Stretching group showed significant improvement in semantic VF & memory while other cognitive functions showed positive results.
Boa Sorte Silva *et al.* (2018)[30] Canada	RCT	n= 109 G= 2 A= 67.5± 7.3 P= Cognitive Deterioration	F= 3 d/wk for 24 wks I= Vigorous- 65–85% HRmax T= 60 min T= Multimodal exercise: aerobic, strength, balance, & stretching with mind-motor training & mind-motor training	Received multiple-modality exercise active control group	VFT (in Dual Tasking: S), CBS cog	Exercisers demonstrated a trend for higher dual task cycle time variability (VF) compared to the control group.

TABLE 1 (part 2 of 5).
Summary of the included studies

Study: Authors (Year) Country	*Design*	*Population[a] (Number, Groups, Age, Participants)*	*Intervention Frequency, Intensity, Time, Type (FITT)*	*Control*	*Language / Cognitive Assessments[b]*	*Summary of Main Findings*
Bossers *et al*. (2015)[31] Netherlands	RCT	n= 109 G= 3 (Combined strength & AE; AE alone) A= 85.7 ± 5.1 P= Mild to severe D	F=4 d/wk for 9wks I= Moderate to high- 50-85% HRR T= 30min T= Lower limb strengthening; Walking	Received 30min one-on-one social visits.	VFT (S) MMSE, 8 WT, DS F & B WMS-R, Face recognition & picture recognition via RBMT, Stroop, Picture completion test, TMT A	Combined strength & AE group showed significant improvement in global cognitive function, visual memory, verbal memory, & executive function. AE alone had better executive function compared to the control group.
Córdova *et al*. (2009)[46] Brazil	Within Subject	n= 48 G= 4 A= 63.8 ± 4.6 P= Regular Exercisers-Females	F= Single bout (Acute) I= 60% AT, 90% AT, 110%AT T= 25min T= Cycling	Remained seated on a cycle for 25min.	VFT TOH, TMT A&B, Simple RT	Acute exercise at 90% of AT exhibited significant improvement in VF, global cognitive functions, memory, & attention. Reduction in simple RT was reported in all 3 exercise groups. Acute exercise at 110% AT only showed improved VF while at 60% AT did not show improvement in any tests.
Cruise *et al*. (2011)[47] Australia	Within Subject	n= 28 G= 2 A= 60.03 ± 9.44 P= Idiopathic PD	F= 2d/wk for 12 wks I= 60-85% HRR T= 60min T= Resistance targeting upper & lower muscle groups & Aerobic comprised of cycling, rowing, treadmill activity	Maintained usual activities.	VFT (S & L), MMSE, PRM; SRM; SWM; SOC	Exercise group showed improvement on semantic VF. Both groups showed improved global cognitive functions.
de Oliveira Silva *et al*. (2019)[32] Brazil	RCT	n= 46 G= 2 A= 77.2 ± 6.96 P= MCI & AD	F= 2d/wk for 12 wks I= Vigorous- 70-80% HRmax T= 60 min T= Multimodal training: aerobic exercises, strength, balance & stretching	Received clinical follow-up but did not perform any physical training.	VFT (S), CDR, CDT Stroop, MMSE	Exercise showed a significant positive effect in VF only for people with MCI compared to their control group. No significant difference for global cognitive functions was observed for people with MCI or AD.
El-Tamawy *et al*. (2014)[48] Egypt	Within Subject	n= 30 G= 2 A= 48.4 ± 6.39 P= Ischemic stroke (3-18months)	F= 3d/wk for 8wks AE followed 25-30 min a physiotherapy program I= NM T= 40-45min T= Pedaling on a bike	Received a physiotherapy program: Stretching exercises, facilitation for weak muscles, strengthening exercise, postural control & balance, functional training, & gait training.	ACER	Exercise showed significant improvement in general cognitive functions & but it did not show change for VF.
Harnish *et al*. (2018)[49] USA	Within Subject	n= 7 G= 2 A= 57.86 ± 14.35 P= Chronic post stroke aphasia	Block1: Cued picture-naming: 4 d/w for 2 weeks for an hour Block2: F= 2d/wk for 12 wks I= 50-70% HRR T= 50min T= Cycling on a bicycle ergometer	Received language therapy & performed stretching.	Cued picture naming	Exercise showed improved naming when used as an adjunct to language therapy.

TABLE 1 (part 3 of 5).
Summary of the included studies

Study: Authors (Year) Country	*Design*	*Population[a] (Number, Groups, Age, Participants)*	*Intervention Frequency, Intensity, Time, Type (FITT)*	*Control*	*Language / Cognitive Assessments[b]*	*Summary of Main Findings*
Helmes & Harris (2017)[53] Australia	Cross-Sectional	n= 68 G= 4 A= 64.2 ± 8.35 P= ND	F= Designed based on self-reported questionnaires I & T= NM T= AE, Resistance, Combined group	Did not participate in any form of exercise.	VFT (L) TOL	AE showed significant beneficial effects on cognition & VF compared to the Resistance & control conditions. Resistance showed significantly improved memory & insignificant improvement in VF compared to non-exercisers.
Hoffman *et al*. (2008)[33] USA	RCT	n= 202 G= 4(supervised AE, home-based AE, Sertraline, Placebo pill) A= 51.7 ± 7.6 P= Major Depressive Disorder	F= 3 d/wk for 16 wks I= 70–85% HRR T= NM T= Treadmill	Received either antidepressant medicine like Sertraline (Zoloft) or Placebo pill	VFT, COWAT Digit Symbol, Ruff 2 & 7, Stroop, TMT; Verbal Paired Associates & Logical Memory	Exercise groups showed significant treatment effects for memory & attention. No significant effect was reported for VF.
Hoffmann *et al*. (2016)[34] Denmark	RCT	n= 200 G= 2 A= 70.5 ± 7.4 P= mild AD	F= 3d/wk for 16 Wks I= Moderate to high (70-80% HRmax) T= 60min T=Multicomponent: Cycling on an ergometer bicycle, cross trainer, & treadmill in a group of 2-5 people;	Received usual treatment with access to memory clinic staff with 4 weeks of adaptation exercise after the termination of the study.	VFT (S & L), SDMT Verbal memory test, Stroop, MMSE	Positive effect was reported on cognitive functions of exercise completers.
Ji *et al*. (2019)[50] China	Within subject	n= 20 G= 1 (4 visits) A= 65.6 ± 1.32 P= ND	F= Single bout (Acute) I= Moderate- 65% HRR T= 25min T= AE- Visits 2-4: 2 Cog Exercise (CE), 3-Physical Exercise (PE) & 4- CE + PE	Visit 1: Sedentary reading control (RC).	Naming using Stroop	Reduced reaction time was reported in CE+PE & PE condition. Improved naming in CE + PE was observed.
Klusmann *et al*. (2010)[35] Germany	RCT	n= 230 G= 3 A= 73.6 ± 4.2 P= ND	F= 3 d/wk for 24 wks I= NM T= 90min T= Exercise group: AE, strength/ flexibility training/Balance/ Coordination- Cycling on an ergometer bike or treadmill Cognitive Group: Computer training	Got instructions to live their habitual life.	VFT (S) MMSE, RBMT (story recall), Free & Cued Selective Reminding Test; TMT A&B; Stroop	Both intervention groups showed better Semantic VF & executive control & significant improvement for immediate/ delayed memory. Control group declined in tests scores after 6 months probably due to healthy aging.
Lautenschlager *et al*. (2008)[36] Australia	RCT	n= 170 G= 2 A= 68.65 ± 8.6 P= Mild MCI & at the risk for AD	F= 3 d/w for 24wks I= Moderate T= 50min T= Walking or strength training activities	Received educational material on memory loss, stress management, healthful diet, alcohol consumption, & smoking but not physical activity.	VFT (L), CERAD-Cog, DST, Word list recall	Exercise group showed better general cognitive functions & memory. While VF did not show significant changes.

TABLE 1 (part 4 of 5).
Summary of the included studies

Study: Authors (Year) Country	*Design*	*Population[a] (Number, Groups, Age, Participants)*	*Intervention Frequency, Intensity, Time, Type (FITT)*	*Control*	*Language / Cognitive Assessments[b]*	*Summary of Main Findings*
McSween *et al*. (2021)[30] Australia	RCT	n= 60 G= 3(Stretching; cycling) A= 66.4 ± 4.6 P= ND	F= Single bout (Acute) I= Moderate (MICE)- 50–70% HRpeak High (HIIE)- 85—95% HRpeak T= MICE: 38min; HIIE: 33min T= Cycling	Stretching for 38min	Associative novel word learning	Participants with lower baseline learning abilities performed significantly better in immediate novel word recall in MICE group compared to the HIIE and control groups.
Nocera *et al*. (2020)[38] USA	RCT	n= 37 G= 3 A= 71.53 ± 1.6 P= ND	F= 3d/wk for 12 wks I= Moderate-50–75% HRR T= 20-45 min T= Aerobic (AE) + Cognitive training (Cog) with focus on executive tasks & AE	Cog: Participated in individual, progressive whole-body stretching/toning exercises & did tasks aimed at cognitive/executive functions	VFT (S &L), Stroop, DS F&B	AE + Cog & AE groups showed significant improvement on VF & global cognitive functions of memory comparing to cog group.
Nocera *et al*. (2017)[12] USA	RCT	n= 30 G= 2 A= 69.45 ± 6.12 P= ND- Sedentary	F= 3 d/wk for 12 wks I= 50-75% HRR T= 20-45min T= Spin Training on a stationary exercise cycle	Performed group balance, stretching, & light muscle toning exercises for 20-45min, 3 d/wk for 12 Wk.	VFT (S & L), HVLT DS F&B	The Spin group showed improved memory functions & semantic VF, less errors of omission and lower activity in the right inferior frontal gyrus compared to the balance group.
Nocera *et al*. (2015)[39] USA	RCT	n= 18 G= 2 A= 71.95 ± 5.24 P= ND- Sedentary	F= 3 d/wk for 12 wks I= 50-75% HRR T= 20-45 min T= Spin Training on a stationary exercise cycle	Got instructed to continue with their normal daily routines by minimal-contact biweekly phone calls to track self-reported levels of PA.	VFT (S, L, & switching)	The exercise group showed significantly improved semantic VF compared to the control group. No significant effects were found for the letter or switching VF.
Nocera *et al*. (2010)[54] USA	Case study	n= 1 G= NA A= 66yrs old female P= PD	F= 3d/wk for 8wks I= 50-75% HRR T= 20min T= Cycling on a stationary bike	NA	VFT (S & L) Picture description In single tasks: MMSE, Stroop, In both single & dual tasks: DS F&B	Exercise showed significant improvement in memory with minimal improvement in letter VF. Motor output during both single & dual task conditions was also improved.
Öhman *et al*. (2016)[40] Finland	RCT	n= 161 G= 3 A= 78.1± 5.3 P= D & moderate or severe AD	F= Home-based Ex: 2 d/wk for 48wks T= 60min Group Ex: 4hrs, 2 d/wk for 48wks I= NM T= AE, endurance, balance, strength, dual-task exercise (e.g., talking while walking)	Received usual care & advice on nutrition & exercise methods	VFT (S), CDT; CDR; MMSE	Group exercise showed no change in global cognitive functions & VF. Home-based exercise showed improved higher cognitive functions.

TABLE 1 (part 5 of 5).
Summary of the included studies

Study: Authors (Year) Country	*Design*	*Population[a] (Number, Groups, Age, Participants)*	*Intervention Frequency, Intensity, Time, Type (FITT)*	*Control*	*Language / Cognitive Assessments[b]*	*Summary of Main Findings*
Rahe *et al*. (2015)[41] Germany	CT- not randomized	n= 30 G= 2 A= 66.73 ± 4.71 P= ND	F= 2d/wk for 6.5 wks I= Moderate T= 90 min T= Cognitive + Cycling on a stationary bike (CPT)	Cognitive training (CT) in group.	VFT (S & L) TMT A & B; DSB; Immediate/delayed Recall, Rey Complex Figure; Modified Taylor Figure; BTA	CT showed significantly enhanced Letter VF. CPT showed improved divided attention & memory functions. More improvement was shown in CPT after a 1-year follow-up but not for CT.
Santos *et al*. (2020)[42] Brazil	RCT	n= 49 G= 2 A= 67 ± 5.5 P= ND	F= 3d/wk for 12 wks I= 10-15 MR T= 50-60 min T= Resistance training (RT)	Did not perform any exercise & were only recommended to maintain a healthy lifestyle.	VFT (S & L), MoCA, Stroop, DS F&B	RT group showed significant improvement in working memory & VF while no statistically significant differences were observed for global cognitive function among the exercisers & control group.
Toots *et al.* (2017)[43] Sweden	RCT	n= 186 G= 2 A= 85.1 ± 7.1 P= AD & Vascular Dementia with mild to severe cognitive impairments	F= 5d/2wks for 16 wks I= Moderate to High (13-14 RM) T= 60min T= Functional exercise	Performed group conversations, singing, listening to music or readings, & looking at pictures/objects while seated.	VFT (S) MMSE; ADAS-Cog	Exercise showed no changes in global cognitive functions or VF.
Vital *et al*. (2012)[51] Brazil	Within Subject	n= 34 G= 2 A= 77.9 ± 6.9 P= AD	F= 3d/wk for 16 wks I= Low intensity T= 60 min T= Weight training	Social Gathering group for relaxation, short walks, reading, poetry, etc.	VFT (S) CDT, BCB	Exercise showed no change in the cognitive & language outcomes.
Won *et al*. (2021)[52] USA	Within Subject	n= 35 G= 2 A= 78 ± 7.1 P= MCI & Healthy	F= 4 d/wk, for 12 wks I= Moderate- 50–60% HRR T= 30 min T= Treadmill walking	Healthy older adults received the same intervention.	Lexical characteristics (cluster size, number of switches, word frequency, age of acquisition, syllable length) of VFT (S & L); COWAT	Frequency and switches of the words produced in letter VF significantly improved across the groups. There were significant associations between exercise-induced increased functional connectivity in cerebellum and improvement in lexical characteristics during letter VF in healthy group and not in MCI group.

[a]In studies with control groups, the total number of participants (n) include the intervention(s) & control groups; Age = groups average.
WMS = Wechsler Memory Scale; CDT = The Clock Drawing Test; BCB = The Brief Cognitive Battery; VFT = Verbal Fluency Task; S = Semantic; L = Letter; HRR = Heart Rate Reserve; RM = Maximum Repetition; CDR = Clinical Dementia Rating; MoCA = Montreal Cognitive Assessment; MMSE = Mini-Mental State Examination; COWAT = Controlled Oral Word Association Test; DKEFB = Delis-Kaplin Executive Function Battery; ADAS-Cog = Alzheimer Disease Assessment Scale- Cognitive section; CERAD-Cog = Consortium to Establish a Registry for Alzheimer Disease- Cognitive Battery; DST = Digit Symbol- Coding Test; HE =Home-Based Exercise; GE = Group-Based Exercise; NM = Not Mentioned; D = Dementia; MCI = Mild Cognitive Impairment; PD = Parkinson's disease; PRM & SRM = Pattern & Spatial Recognition Memory; SWM = Spatial working memory; SOC = Stockings of Cambridge; PDQ-39 = Parkinson's Disease Questionnaires; GDS = Geriatric Depression Scale; QoL = Quality of life; ACER = Addenbrooke's Cognitive Examination- Revised; 8WT = 8 Words Test direct recall/recognition; BTA = Brief Test of Attention; DS F&B = Digit Span Forward& Backward; TMT = Trail Making Test; TUAG = Timed-Up-& Go.

Cued picture naming,[49] picture description,[45,54] and picture completion[29] were also measured. A single study assessed only Addenbrooke's cognitive Examination-Revised (ACE-R) in which VF, language comprehension, repetition, and naming were assessed.[46] The cognitive measures with at least one verbal component used in these studies were Word List, Story Recall, Immediate and Delayed Recall, Rey Auditory Verbal Learning Test, or Verbal Paired Associates & Logical Memory for Verbal Memory test,[28,29,31,34,36,44] Stroop Word Interference Test,[28,29,31-34,45,54] Digit Span Forward & Backward,[28,31,33,45,54] Visual Memory Span Forward & Backward,[31] AD Assessment Scale-Cognitive, Clinical Dementia Rating or other Brief Cognitive Examinations,[28,30,32,35,40,43,44,51] or the MMSE.[31,32,34,40,43,44,54] The number of language and cognitive assessments per population is shown in Figure 3.

DISCUSSION

This scoping review aimed to identify the effect of exercise on language performance in healthy aging adults and adults with stroke or neurodegenerative conditions. In line with previous reviews assessing the effect of exercise on various aspects of cognitive functions[4,5,14] and language performance,[16] we found that exercise can have positive effects on language performance in the addressed populations, as evidenced by the improved performance on VF and naming tasks. However, findings were inconsistent for older adults with stroke and neurodegenerative conditions. In older adults with PD,[45,47,54] dementia,[31] mild AD,[34] MCI,[29,32,44] or cognitive deterioration,[30] exercise interventions could positively influence VF[29,30,32,44,47,54] and picture description,[43] while no significant change was observed in VF tasks for older adults at risk of[36] or with AD,[28,40,43,51] or with major depression disorder.[33] In people with stroke, naming[49] showed improvement following exercise, while VF[48] remained unchanged.

Research on language performance is largely based on the use of a variety of word processing and production paradigms susceptible to age-related changes including VF and naming tasks. Generating words for such tasks relies on different networks across interconnected brain regions within and between hemispheres that engage in several coordinated cognitive and linguistic processes.[55] The cognitive ability of selection, retrieval, and production of appropriate lexical items is mostly associated with frontal, prefrontal, and temporal neural substrates.[3,56] Verbal word planning and articulation depend on the interactions between the language dominant hemisphere's lateral frontal cortex, including posterior temporal and parietal regions and more anterior regions, such as the inferior frontal, anterior insula, and the motor cortex.[57] Aging influences different cognitive domains and

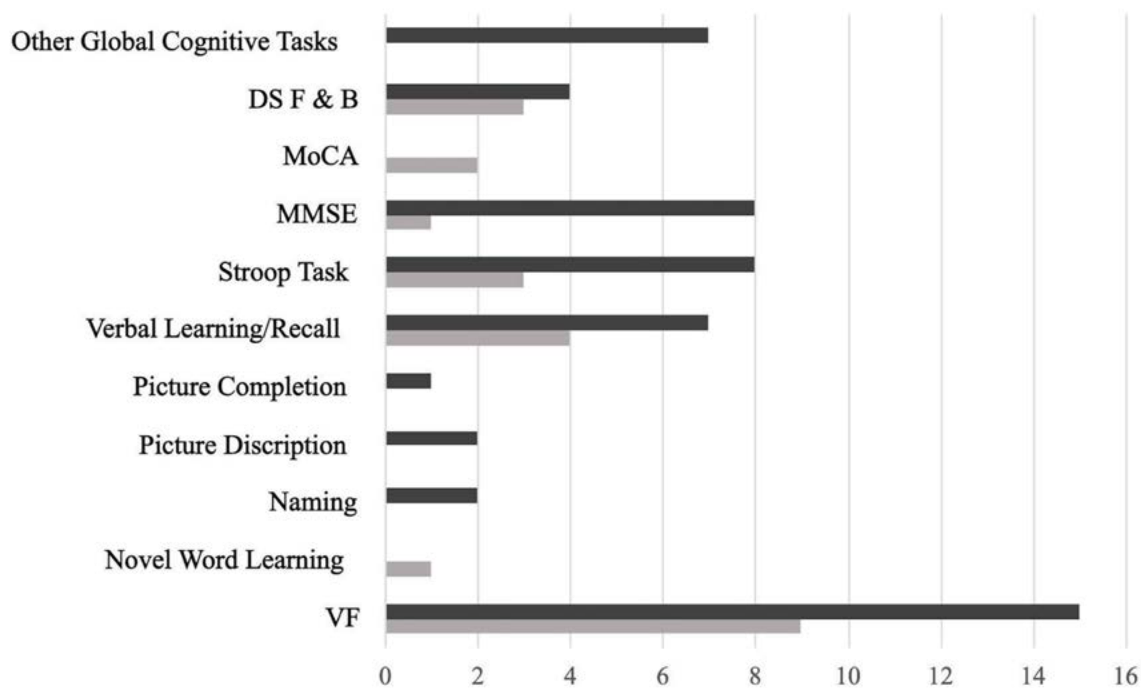

FIGURE 3. Language and cognitive assessments
Number of Language & Cognitive Assessments per population: Light colour = healthy aging adults; Dark colour = Adults with Stroke or Neurodegenerative Conditions.
Other Global Cognitive Assessments include Cambridge Cognitive Examination (Brazilian Version); Alzheimer's disease assessment scale Cognitive; Cambridge Brain Sciences Cognitive Baxter; Addenbrookes's Cognitive Examination-Revised; The Brief Cognitive Battery.
DS F&B = Digit Span Forward and Backward; DS F & B = Digit Span Forward & Backward; MoCA = Montreal Cognitive Assessment; MIMSE = Mini-Mental State Examination; VF = Verbal Fluency.

effortful executive processing such as inhibition or speed processing, mediated by the frontal and prefrontal cortices and required for VF.[6] Evidence indicates that exercise could improve cognitive and executive performance mediated by these brain regions.

Exercise programs have shown significant, but selective, benefits for cognition, with the greatest fitness-induced gains appearing in executive-control processes[4] mediated by frontal and prefrontal brain regions which are essential for word retrieval. Fluent verbal production demands the transmission process between the semantic–verbal memory and phonological processing of a word with the involvement of executive processes.[58] VF measures are considered to place comparable demands on linguistic processes and effortful executive processes[8,59] which were found to improve by exercise.[4] Both semantic and letter VF tasks require efficient verbal retrieval and recall, as well as self-monitoring, deliberate self-initiation, and appropriate inhibition of responses.[59] Like VF, naming also relies on executive functions while engaging visual perceptual-spatial functioning.[60] A meta-analysis[4] demonstrated that cardiovascular exercise had a large effect size (g = 0.68) on planning, inhibition, and scheduling effortful mental procedures involved in VF. In line with this, the present review showed that studies in healthy aging adults improved semantic VF,[12,35,39] letter VF,[41,53] or both VF measures,[27,38,43,46] and naming[27,50] following exercise.

Very few studies have explored the effects of exercise on language performance in older adults with stroke.[13] We found only two studies on exercise in post-stroke patients that investigated the effect of cardiovascular exercise on naming,[49] VF, and global cognitive functions.[48] One study showed enhancement in naming in post-stroke aphasia.[49] The other reported significant improvement in cognitive functions with no change in VF.[48] Hence, further investigation is required to evaluate the role of exercise in language improvement in post-stroke aphasia.

In this review, findings for older adults with neuro-degenerative conditions were inconclusive. Several studies showed positive results in semantic VF in people with MCI,[29,30,32,44] PD,[47,54] and mild-to-severe dementia[29] following exercise. Other exercise programs showed no change in semantic or letter VF in people with AD or dementia,[34,40,43,51] or people with MCI at risk of AD.[36] Neurodegenerative conditions like AD or other types of dementia can impact visuospatial processing including semantic memory, which was shown to be minimally (g = 0.426) affected by exercise.[4,5] Another reason why exercise was less effective in people with AD or other types of dementia could be the existing degraded semantic store's integrity reflected in the impaired semantic VF.[59,61,62] A meta-analysis of 153 studies with 15,990 participants[59] found that naming and semantic VF were considerably more impaired than letter VF in people with dementia of the AD type. Overall, alterations in the structure or content of semantic knowledge in people with AD and other types of dementia[61,62] might interfere with the effect of exercise on VF, especially on semantic VF. However, given that cognitive and language performance tends to decline in AD and other types of dementia,[63] maintained cognitive functions following exercise protocols can be considered beneficial in such conditions.

In recent years, a large body of research exists on the effect of both acute and chronic exercise programs on cognition. Acute exercise showed improvement in attentional and memory resource allocation, hence benefitting executive control function in young[64] and older individuals.[4] Better vocabulary learning, recall, and retrieval were reported as the result of acute cardiovascular exercise in young (20.5 ± 0.5)[65,66] and older adults (66.4 ± 4.6).[37] The within-subject acute exercise studies included in the present review also reported a significant improvement in VF, global cognitive functions, memory, and attention, as well as a reduction in reaction times, following 25 minutes of acute cardiovascular exercises in older adults.[46,50]

In addition to acute exercise, chronic exercise paradigms induced improvement in cognitive and executive functions[4] as well as VF.[12,38] Chronic cardiovascular exercise has been linked to increased grey matter volumes in the hippocampus and prefrontal cortex,[13] as well as improvements in the prefrontal white matter tracts.[67] The hippocampus and prefrontal cortex are both involved in memory,[68] executive functioning,[69] and language processing.[70] Additionally, hippocampus degeneration has been reported in healthy aging[71] and in the pathogenesis of a variety of neurological conditions including dementia and major depressive disorder.[72] It seems that most exercise-induced neuroplasticity effects are associated with changes in the frontal and prefrontal cortex[13] that play a pivotal role in executive functions and working memory processes[68,69] involved in linguistic processing.

Exercise-induced changes in the brain can promote neuroplasticity[73] which may also contribute to changes in the affected language networks.[74,75] Brain-Derived Neurotrophic Factor (BDNF) is a neuroplasticity biomarker that was found to be affected by exercise paradigms.[15] Studies using non-invasive techniques indicated that exercise may be able to stimulate neuroplastic mechanisms such as neurogenesis, and increased basal BDNF levels.[76] Consistent with this finding, two of the studies also reported changes in BDNF levels and improved naming[49] and cognitive functions[48] in people with ischemic stroke following eight weeks of aerobic exercise. While there is evidence showing exercise increases BDNF levels,[15,77] the association between peripheral BDNF levels and cognitive functions requires more investigation.

The extent to which exercise can influence cognition is thought to be modulated by exercise parameters (i.e., FITT) and the timing of outcome assessment relative to administrating exercise, among many other factors. In addition to exercise protocols and methodological factors, inter- and intraindividual variability could also be a critical moderator in the response to exercise aimed at improving language. McSween and colleagues[37] found that individuals with lower baseline word learning abilities appeared to learn vocabulary more effectively than those with better baseline word learning abilities following a single bout of moderate and high-intensity cycling.

To summarize, language tasks that place more demands on linguistic processes and effortful executive functions mediated by frontal and prefrontal brain regions[8,59] seemed to be more responsive to the effect of exercise.[4]

Limitations

We identified several limitations in the present review. Studies often used cognitive measures that may not have been sensitive enough to best capture changes in the studied population. For example, in studies on AD and dementia, validated cognitive measures, such as the MMSE[33,34] or other brief cognitive batteries,[49] might not reflect exercise-induced changes.[78] Furthermore, most studies reported overall scores, especially on measures such as MoCA or MMSE, with no record of individual scores for each subcategory. This made the analysis of the impact of exercise on the language component(s) challenging. Overall, heterogeneity in the studied populations and outcome measures may have affected the magnitude of the observed effect and challenged the generalizability of the findings.

CONCLUSION

Examining the effects of exercise on language performance is a relatively new area of research and more research is needed on different language domains. More particularly, neuroimaging studies can further examine the interactive effect of the underpinning neural mechanisms of exercise-induced changes in language production per individual. Studying how the cortical activities change during language tasks following exercise can provide valuable insights into designing new exercise-based treatments.

This scoping review provides new evidence on the effect of exercise paradigms on language performance in aging adults with and without language impairment. However, it is still unknown if the amount of the effect of exercise on language performance is therapeutically meaningful for persons with stroke or neurodegenerative conditions.

Overall, comprehending, analyzing, and implementing effective interventions which are feasible, low-cost, minimal risk, and non-pharmaceutical require more in-depth research on exercise and neurocognitive functions.

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CONFLICT OF INTEREST DISCLOSURES

We have read and understood the *Canadian Geriatrics Journal*'s policy on conflicts of interest disclosure and declare that we have none.

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APPENDIX A. Search strategy using 18 key terms

1. language performance
2. language production
3. language comprehension
4. verbal fluency
5. semantic association
6. lexical retrieval
7. lexical access speed
8. lexical access
9. vocabulary receptive
10. vocabulary expressive
11. vocabulary production
12. word production
13. 1 OR 2 OR 3 OR 4 OR 5 OR 6 OR 7 OR 8 OR 9 OR 10 OR 11 OR 12
14. exercise
15. aerobic exercise
16. cardiovascular exercise
17. resistance exercise
18. fitness
19. physical fitness
20. 14 OR 15 OR 16 OR 17 OR 18 OR 19
21. 13 AND 20

APPENDIX B (part 1 of 2). Extraction sheet

Research Question: What is currently known about the effect of exercise on language performance in healthy adults, as well as in individuals with neurological conditions, that impact on language and communication?

Administrative	*Data*	*Reviewer 1*	*Reviewer 2*
	Publication Code		
Identity of Publication	Title		
	Field (author affiliations)		
	Year of Publication		
	City/Country/ Setting		
	Type of publication		
Introduction	Abstract		
	Aim of Study/Research Question		
Method	Study Design (eg. Case study, RCT, etc.)		
	Type and Number of Participants		
	If not healthy, type of disability		
	Age (Mean (SD))		
	Gender (Male/Female)		
	Inclusion and Exclusion Criteria		
	Participants Groups		
	Control Group		
	Type of Intervention		
	Intervention Design		
	Baseline Measurement		
	Cardiovascular Fitness Measurement		
Outcome	Language Measurement		
	Cognition Measurement		
	Other Outcome Measurements		
	Time of assessment		
Body Functions	b1- Mental Functions		
	b2- Sensory Functions and Pain		
	b3- Voice and Speech Functions		
	b4- Functions of the Cardiovascular, Haematological, Immunological and Respiratory Systems		
	b5- Functions of the Digestive, Metabolic and Endocrine Systems		
	b6- Genitourinary and Reproductive Functions		
	b7- Neuromusculoskeletal and Movement-Related Functions		
	b8- Functions of the Skin and Related Structures		

APPENDIX B (part 2 of 2). Extraction sheet

Administrative	*Data*	*Reviewer 1*	*Reviewer 2*
	Publication Code		
Body Structures	s1- Structures of the Nervous System		
	s2- The Eye, Ear, and Related Structures		
	s3- Structures involved in Voice and Speech		
	s4- Structures of the Cardiovascular, Immunological and Respiratory Systems		
	s5- Structures related to the Digestive, Metabolic, and Endocrine Systems		
	s6- Structures related to the Genitourinary and Reproductive Systems		
	s7-Structures Related to Movement		
	s8- Skin and Related Structures		
Activities and Participation	d1- Learning and Applying Knowledge		
	d2- General Tasks and Demands		
	d3- Communication		
	d4- Mobility		
	d5- Self Care		
	d6- Domestic Life		
	d7- Interpersonal interactions and Relationships		
	d8- Major Life Areas		
	d9- Community, Social and Civic Life		
Environment Factors	e1- Products and Technology		
	e2- Natural Environment and Human-Made changes to environment		
	e3- Support and Relationships		
	e4- Attitudes		
	e5- Services, Systems and Policies		
General	Additional General Comments		
	Study limitations		

APPENDIX C (part 1 of 3). ICF (2001) codes for language and cognitive assessments

Study: Authors (Year) Country	*Language Assessments [a]*	*Cognitive Assessments [b]*
Alfini *et al*. (2019)[44] USA	COWAT: VFT (Semantic: Animals): b167 Mattis Dementia Rating Scale-2 (DRS-2- global cognitive function and risk of dementia): b167 Logical Memory and Letter-Number Sequencing subtests of the WMS-III: b167 RAVLT (Verbal working memory and delayed-recall): b167 MMSE: b167	Mattis Dementia Rating Scale-2(DRS-2- global cognitive function and risk of dementia): b114, b140, b144, b164 MMSE: b160-b164 SDMT (Attention and processing speed): b140, b144, b147, b164 Logical Memory and Letter-Number Sequencing subtests of the WMS-III: b144 RAVLT (Verbal working memory and delayed-recall): b144
Altmann *et al*. (2016)[45] USA	Picture description: b167, b1681, b16810 DS F&B: b167 Stroop: b167	Simple attention: b140 Picture description: b140, b1440-back: b144 DS F&B: b140, b144, b164 Stroop: b140, b164
*Ansai & Rebelatto (2015)[27] Brazil	VFT (NM): b167 MoCA (language-Naming): b167 Dual task: TUGT associated with simultaneous cognitive task, i.e., repeating the days of the week in reverse order beginning with Sunday: b167	MoCA: Attention b140, b144 CDT: b164, b176 Dual task: TUGT associated with simultaneous cognitive task, i.e., repeating the days of the week in reverse order beginning with Sunday: b140, b144, b164
Arcoverde *et al*. (2014)[28] Brazil	VFT (Semantic-Animal): b167 DS F&B: b167 RAVLT: b167 Stroop: b167	Cambridge Cognitive Examination (Brazilian Version): b164 CDT: b164, b176 TMT A: b140, b144, b164 DS F&B: b140, b144, b164 RAVLT: b144 Stroop: b140, b164
Baker *et al*. (2010)[29] USA	VFT (Semantic & Letter): b167 Story Recall: b167; b1681 Stroop: b167	TMT B: b140, b144, b164 Task Switching: b140, b1402(Dividing attention), b144 Delayed-Match-To-Sample: b144, d160 focusing attention Story Recall: b144 Stroop: b140, b164
Boa Sorte Silva *et al*. (2018)[30] Canada	VFT (In Dual Tasking: Animals, Vegetables, Countries): b167 Cambridge Brain Sciences cognitive battery (Global and domain-specific cognitive functioning): b167	Cambridge Brain Sciences cognitive battery (Global and domain-specific cognitive functioning): b114, b140, b144, b164
Bossers *et al*. (2015)[31] Netherlands	VFT (Semantic & Letter): b167 Visual memory span forward & backward test (WMS-R): b167 Eight-words test direct recall/recognition: b167 DS F&B: b167 Picture completion test (Groningen Intelligence Test): b167 Stroop: b167 MMSE: b167	MMSE: b160-b164 Rivermead Behavioural Memory Test (Face & picture recognition-Visual memory): b144 TMT A: b140, b144, b164 Visual memory span forward & backward test (WMS-R): b144 Eight-words test direct recall/recognition: b144 DS F&B: b140, b144, b164 Picture completion test (Groningen Intelligence Test): b140, b144 Stroop: b140, b164
*Córdova *et al*. (2009)[46] Brazil	VFT (Semantic- animal): b167	TOH: b140, b164, b1646 (Problem-solving)MTA&B: b140, b144, b164 Simple Response Time Test: b140, b164
Cruise *et al*. (2011)[47] Australia	VFT (Semantic-animal & Letter -FAS): b167	Pattern and Spatial Recognition Memory: b140, b144, b164 Spatial working memory: b144, b164 Stockings of Cambridge: b140, b164

APPENDIX C (part 2 of 3). ICF (2001) codes for language and cognitive assessments

Study: Authors (Year) Country	*Language Assessments* [a]	*Cognitive Assessments* [b]
de Oliveira Silva *et al*. (2019)[32] Brazil	VFT (Semantic- Animals): b167 CDR: b167 Stroop: b167 MMSE: b167	CDR: b164 MMSE: b160, b164 CDT: b164, b176 Stroop: b140, b164
El-Tamawy *et al*. (2014)[48] Egypt	NM ACER: b167	ACER: b164
Harnish *et al*. (2018)[49] USA	Cued picture naming: b167	Cued picture naming: b144
*Helmes & Harris (2017)[53] Australia	VFT- Letter using C, P, and L form Benton Controlled Oral Word Association Test: b167	TOL: b164
Hoffman *et al*. (2008)[33] USA	VFT (Semantic- animal): b167 Controlled Oral Word Association Test (Letter: CFL, PRW): b167 Verbal Paired Associates & Logical Memory Subtests from WMS: b167 Stroop: b167	Digit Symbol Subtest from WAIS-R: b140, b144, b147, b164 Ruff 2 & 7 Test: b140, b144 TMT: b140, b144, b164 Verbal Paired Associates & Logical Memory Subtests from WMS: b144 Stroop: b140, b164
Hoffmann *et al*. (2016)[34] Denmark	VFT (Letter & semantic): b167 Verbal memory test (10 words recalled three times, immediate and delayed recall): b167 Stroop: b167 MMSE: b167	SDMT: b140, b144, b147, b164 MMSE: b160-b164 Verbal memory test (10 words recalled three times, immediate and delayed recall): b144 Stroop: b140, b164
*Ji *et al*. (2019)[50] China	Stroop (reading colour names): b167	Stroop (reading colour names): b140, b164
*Klusmann *et al*. (2010)[35] Germany	VFT (Semantic: Animal/food): b167 Boston naming test: b167 MMSE: b167 Word List Recall: b167 Rivermead Behavioural Memory Test (Immediate/delayed story recall): b167, b1681 Stroop Test: b167	MMSE: b160, b164 Free and Cued Selective Reminding Test: b144 Boston naming test: b144 Reitan TMT A&B: b140, b144, b164 Word List Recall: b144 Rivermead Behavioural Memory Test (immediate/delayed story recall): b144 Stroop Test: b140, b164
Lautenschlager *et al*. (2008)[36] Australia	VFT (Letter -FAS) measured by DKEFB: b167 ADAS-Cog: b167 Word list recall: b167	ADAS-Cog: b164 Digit Symbol Coding Test: b140, b144, b147, b164 Word list recall: b144
*McSween *et al*. (2021)[30] Australia	Associative novel word learning Task	NA
*Nocera *et al*. (2020)[38] USA	VFT (Letter & Semantic): b167 Stroop: b167 DS F&B: b167	Stroop: b140, b164 Trail making test of the D-KEFS: b140, b144, b164 Computerized n-back: b140, b144, b164 DS F&B: b140, b144, b164
*Nocera *et al*. (2017)[12] USA	VFT (Letter & Semantic): b167 DS F&B: b167 Hopkins Verbal Learning Test: b167	DS F&B: b140, b144, b164 Hopkins Verbal Learning Test: b144

APPENDIX C (part 3 of 3). ICF (2001) codes for language and cognitive assessments

Study: Authors (Year) Country	*Language Assessments [a]*	*Cognitive Assessments [b]*
*Nocera *et al*. (2015)[39] USA	VFT (Letter & Semantic): b167 switching VF: animals and boys' names or items of clothing and girls' names: b167	Switching VF: animals and boys' names or items of clothing and girls' names: b 140 attention functions, b1401 Shifting attention,
Nocera *et al*. (2010)[54] USA	VFT (Semantic & Letter): b167 Picture description: b167, b1681, b16810 MMSE: b167 Stroop: b167 DS F&B: b167	MMSE: b160-b164 Stroop: b140, b164 DS F&B: b140, b144, b164
Öhman *et al*. (2016)[40] Finland	VFT (Semantic): b167 MMSE: b167	CDT: b164, b176 Clinical Dementia Rating: b114, b140, b144, b164 MMSE: b160-b164
*Rahe *et al*. (2015)[41] Germany	VFT (Semantic: Animals/Supermarket items Letter: using COWA): b167 Verbal memory: Subsets of immediate/delayed recall from DemTect Test: b167	Verbal memory: Subsets of immediate/delayed recall from DemTect Test: b144
* Santos *et al*. (2020)[42] Brazil	VFT (Letter & Semantic): b167 MoCA: b167 Stroop: b167 DS F&B: b167	MoCA: b140, b144 Stroop: b140, b164 DS F&B: b140, b144, b164
Toots *et al*. (2017)[43] Sweden	VFT (Semantic): b167 MMSE: b167 ADAS-Cog: b167	MMSE: b160-b164 ADAS-Cog: b164
Vital *et al*. (2012)[51] Brazil	VFT (Semantic): b167 BCB: b167	CDT: b164, b176 BCB: b144, b164
Won *et al*. (2021)[52] USA	COWAT: VFT (letter: F,A,S & Semantic: Animals): b167	NA

[a&b]ICF Codes: b140 = Attention Functions; b144 = Memory Functions, b147 = Psychomotor Functions; b160 = Thought Functions; b164 = Higher-Level Cognitive Functions; b167 = Mental Functions of Language; b1681 = Expression of language; b16810 = Expression of spoken language; b176 = Mental Function of Sequencing Complex Movements.

Asterisk (*) = populations without any neurological disorders; VFT = Verbal Fluency Task; NA = Not Applicable; TUAG = Timed-Up-and Go; MoCA = Montreal Cognitive Assessment; MMSE = Mini-Mental State Examination TMT = Trail Making Test; NM = Not Mentioned; TOL = The Tower of London test; TOH = The Tower of Hanoi Test; COWT = Controlled Oral Word Association Test; D-KEFS = Delis-Kaplan Executive Function System; DS F&B = Digit Span Forward & Backward; RAVLT = Rey Auditory Verbal Learning Test; SDMT = Symbol Digit Modalities Test; Stroop = Stroop Colour and Word Test; CDT = Clock Drawing Test; ACER = Addenbrookes's Cognitive Examination-Revised; BCB = The Brief Cognitive Battery; WMS-III = Wechsler Memory Scale-III; CDR = The Clinical Dementia Rating; ADAS-Cog = Alzheimer's disease assessment scale Cognitive.