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A systematic review of the relationships amongst older adults' cognitive and motor speech abilities

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A B S T R A C T

Age-related differences in motor speech performance may be only partially explained by physiological factors. In this systematic review we investigated the extent to which cognition is related to older adults' motor speech production. PsycInfo, PubMed, Web of Science, and the Cochrane Library were last searched on 1st October 2024. Eligible studies involved healthy older adults, and/or those with mild cognitive impairment (MCI), with an average age of 60 or above. Study quality was formally evaluated and results presented via a narrative synthesis. In total, there were 22 eligible studies identified including 747 older adults. Ten of eighteen studies investigating attention/executive abilities reported significant relationships with motor speech subprocesses in 571 of 661 participants. Relationships between other cognitive abilities and motor speech outcomes were also reported, however, there were significant gaps in the literature and heterogeneity in the measurements used. In addition, only five studies contained the highest quality evidence. Cognition, and potentially executive abilities specifically, may affect speech articulation in healthy aging and in MCI. Further research implementing a range of tasks is required to better understand the trajectory of age-related changes to cognition and motor speech production.

1. Introduction

Aging is associated with biomechanical as well as neurological changes to speech and language (Caruso & Mueller, 1997), and both are important for successful communication (Hooper & Cralidis, 2009). Cognitive explanations have been widely investigated in relation to effects of aging on language production (e.g. Mortensen et al., 2006; Wright, 2016). However, physiological explanations dominate the literature on the differences between young and older adults' motor speech production, despite a suggested role for cognition (Sadagopan & Smith, 2013; Zraick et al., 2006). This systematic review aims to determine the relationship/s amongst cognitive and motor speech abilities in adults aged 60 years and over, by gathering and evaluating relevant existing evidence.

1.1. Speech production

Producing speech is a complex, multistage process that begins with the intention to communicate a message and ends in articulation (Tremblay et al., 2019a). The term 'speech production' has therefore been used to refer to language and/or motor speech

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production (e.g. Mortensen et al., 2006; Parrell & Houde, 2019), which can broadly be distinguished as the beginning and the end of the speech production process (Hickok, 2012). Language production concerns the early stages of forming a word or sentence (e.g. Levelt et al., 1999) and is usually described as involving linguistic or higher-level cognitive processes. Motor speech production refers to the motoric processes involved in producing speech sounds. The term 'motor' refers to the part of the nervous system – the 'motor system' – that controls voluntary movements; 'speech' is the tool used to express verbal language through producing sounds that are then perceived and processed by listeners (Borden, 1994; Freed, 2018). This process can be further subdivided into segmental and non-segmental features. Segmental features refer to the production of identifiable speech sounds involving the oral articulators – lips, tongue and velum, as well as the laryngeal and respiratory system. Non-segmental or supra-segmental features apply to units larger than individual segments. These include prosodic features such as stress, intonation, pause or rhythm which are produced by manipulating pitch, loudness, segment duration and silence (perceived as pauses), and voice quality. Production of these features also rely on the oral articulators as well as the respiratory and laryngeal systems. For the purposes of this review, any studies focused on the production of speech sounds, including non-speech tasks such as syllable repetitions, have been categorized as investigating 'articulation'. In contrast, prosody, voice quality, and non-speech assessments of the respiratory or phonatory subsystems have been classified as 'non-segmental features'.

From a theoretical perspective, motor speech production involves several subprocesses that proceed in serial order at the neurobiological level, including speech motor planning or programming, response selection, sequencing, timing, execution, and sensorimotor integration (Tremblay et al., 2019a). Given this complexity (Van Der Merwe, 2021), it is a challenge for models to represent the entire process from conceptualization to articulation, which requires cognition, language processing, and motor faculties (Postma, 2000). Instead, most speech production models tend to focus either on language or speech motor control, resulting in models that are uncoordinated (Smith, 2006). Psycholinguistic models focus conceptually on higher level language processes, predominantly at the level of words/lemmas and phonology (Hickock, 2012). For example, Levelt et al.'s (1999) theory of lexical access predicts that words are formulated through a feedforward process involving conceptual preparation, lexical selection, and morphological and phonological encoding. The authors state that language production ends in articulation, but a thorough explanation of the articulatory process is beyond the scope of their theory. On the other hand, models of speech motor control (e.g. The Directions into Velocities of Articulators, DIVA; Guenther, 1994; Guenther & Hickock, 2015) minimize the role of language processing (Smith, 2006), focusing on motor programs and sensorimotor integration, primarily in the form of auditory and somatosensory feedback, for executing speech sounds. Interestingly, the recently developed laryngeal DIVA model (LaDIVA; Weerathunge et al., 2022) predicts that the laryngeal and articulatory subsystems may interact differently with auditory and somatosensory feedback (Weerathunge et al., 2022). These authors suggest that laryngeal and articulatory domains should be considered separately in future research, highlighting a need for a greater theoretical understanding of motor speech production. Despite the existence of several speech production models (for a review of speech monitoring models, see Postma, 2000), most are based on data from typical young adult speakers (Tucker et al., 2021). Thus, the effects of aging on speech abilities requires greater theoretical attention.

Consideration of how motor speech production might change with age raises the question of whether cognition or, more specifically, age-related cognitive decline, could affect older adults' motor speech abilities. Indeed, data has linked cognition to both language and motor speech production in typical young adult speakers (e.g. Barker et al., 2020; Kent, 2000, 2004), with Kent (2004; p. 3) going as far as to describe motor speech production as a "cognitive-motor accomplishment". However, from a theoretical perspective, the potential role of cognition is absent from neurocomputational models of speech motor control (e.g. Guenther,1994; Guenther & Vladusich, 2012). Furthermore, while an executive monitoring system is included in some psycholinguistic models (e.g. Levelt et al., 1999), generally, the role of specific cognitive abilities is underspecified, making it difficult to identify potential predictors of change when speech production breaks down. A more general theory that may enable the linkage of cognition to motor speech production is Node Structure Theory (NST; MacKay, 1982). It is postulated that execution of an action relies on activation in the mental and muscle movement systems, through a process of spreading activation (Dell, 1986). Frequent activation increases the strength of priming between the mental and muscle systems, resulting in, for example, faster articulation rate. This suggests a potential theoretical connection between cognition and motor speech production. However, we currently lack evidence for this assumption. To date, in typical aging, the role of cognition has been researched more thoroughly in relation to language processing than to motor speech production (e.g. Barker et al., 2020; Burke et al., 2000; Marini & Andreeta, 2016; Shafto et al., 2007).

1.2. Cognitive aging

Age-related changes to the structure and functioning of the brain can affect cognitive ability (e.g. Reuter-Lorenz & Park, 2014). 'Fluid' cognitive abilities such as speed of processing, visuospatial abilities, executive functioning, and short-term/working memory typically show gradual declines across the adult lifespan. In contrast, 'crystallized' abilities such as semantic or verbal knowledge continue to show improvement or remain relatively stable (Park et al., 2002; Salthouse, 2012, 2019). In relation to speech production, theories of cognitive aging predominantly attempt to explain language difficulties. For instance, the inhibition deficit hypothesis (Campbell et al., 2020; Hasher & Zacks, 1988; Lustig et al., 2007) explains off-topic speech due to difficulty inhibiting irrelevant information (Gold & Arbuckle, 1995). Declines in working memory (the temporary processing and storage of information; e.g. Baddeley, 2012) are linked to producing shorter, simpler sentences (Kemper, 1993). Lexical access difficulties, including slips of the tongue (e.g. coffee cot vs coffee pot) and tip-of-the-tongue moments (i.e. the inability to produce a known word), are well-documented in older adults' speech through self-reports (Lovelace & Twohig, 1990) and behavioural and neuroimaging evidence (Burke et al., 2000; Galdo-Alvarez et al., 2009; Mortensen et al., 2006; Shafto et al., 2007). Mortensen et al. (2006) suggest that the transmission deficit hypothesis (Mackay & Burke, 1990; Taylor & Burke, 2002) - reduced priming - best explains lexical retrieval difficulties, with aging resulting in weakened connections between word lemmas and word forms. There are therefore established links between cognition and language production deficits in aging (Barker et al., 2020; Wright, 2016). Language tasks, such as naming and verbal fluency (i.e. say as many words as possible starting with the letter 's' in 60 seconds), are frequently included in neuropsychological testing to assess cognitive functioning (e.g. Holtzer et al., 2008). Therefore, language may also be viewed as a cognitive process (Barker et al., 2020; Perlovsky & Sakai, 2014). Age-related differences are also observed in motor speech outcomes (see Section 1.3); however, this is rarely discussed when considering the impact of aging on cognition and language production (e.g. Burke & Shafto, 2004), despite the interaction between speech and language.

1.3. Age-related differences between young and older adults' motor speech abilities

Beyond the language deficits outlined in Section 1.2, older adults' motor speech abilities may also differ from that of typical young adult speakers. Distinct from language planning, speech motor planning involves phonological encoding and preparation in the speech motor system to execute a series of actions in the correct order (Tremblay et al., 2019b). Speech motor planning difficulties are generally associated with apraxia of speech (Utianski & Josephs, 2023). However, there is some evidence to suggest that typical aging could also be associated with poorer speech motor planning. For example, research has shown that older adults have greater difficulty than younger adults with articulatory accuracy when repeating complex non-words (Sadagopan & Smith, 2013) and syllables (Bilodeau-Mercure & Tremblay, 2016; Tremblay et al., 2019a), potentially suggesting speech motor planning difficulties. Similarly, older adults can be differentiated from younger adults based on both phonatory, respiratory and articulatory measures (Kuruvilla-Dugdale et al., 2020; Rojas et al., 2020; Tucker et al., 2021). In terms of voice features, it is generally agreed that physiological changes to the larynx, vocal cords, and respiratory system underlie qualitative differences in phonatory characteristics (Caruso & Mueller, 1997), such as increased breathiness or hoarseness and changes to pitch, loudness and vocal effort (Rojas et al., 2020). Physiological changes might also be the cause of some of the articulatory changes that have been observed in older adults. For example, older adults generally produce speech more slowly than younger adults. Speed of articulation can be expressed in various ways: perceptually as tempo, and instrumentally either as articulation or speech rate. Articulation rate purely reflects the time taken to articulate the words within a message. Speech, or speaking rate, also includes pauses contained in the message and thus reflects the perceptual measure of tempo more closely. It should be noted that the inclusion of pauses results in these measures potentially being influenced by higher-order linguistic processes such as planning or word finding. Nevertheless, slower speech has been identified in older adults across all measures. Both novice and expert listeners have reported reduced tempo (e.g. Parnell & Amerman, 1987; Ryan & Burk, 1974). Similarly, Duchin and Mysak (1987) found that speech rate during conversational, sentence repetition, and oral reading tasks decreased across the adult lifespan. Karlsson and Hartelius (2021) reported that articulation rate was slower in older compared to younger adults when asking participants to rapidly repeat syllables. In addition to rate measures, kinematic measures of tongue movements indicate that older adults produce slower movements, resulting in poorer intelligibility of speech (Kuruvilla-Dugdale et al., 2020).

Interestingly, orofacial muscular changes, such as weakening of the jaw, tongue, and lips, do not fully explain some of the observed differences in articulatory movement speed (Goozée et al., 2005; Mefferd & Corder, 2014; van Brenk et al., 2014). It has been hypothesized that age-related cognitive decline might also play a role (van Brenk et al., 2014). One suggestion is that decline in working memory processes results in the inaccurate production of speech sounds (Sadagopan & Smith, 2013). However, further research is necessary to fully understand which, and to what extent, age-related changes to cognitive abilities affect the execution of speech.

1.4. The potential role of cognition in older adults' motor speech production

Whilst we lack sufficient support for the assumption that cognition impacts on motor speech behaviour in healthy older adults, evidence from people with cognitive impairment suggests that differences in global cognitive functioning may in fact be reflected in motor speech production. For example, Themistocleous et al. (2020) found that patients with Mild Cognitive Impairment (MCI) had weaker voice quality and slower articulation rates than age-matched older adults, suggesting that declines to global cognitive functioning could be indicative of motor speech differences and vice versa. Also, speech analysis is increasingly being used as a diagnostic predictor of pathological aging (e.g. Martínez-Nicholás et al., 2021). Most researchers attempt to identify the presence of Alzheimer's Disease (AD) and, less often, MCI (de la Fuente Garcia et al., 2020), by comparing differences in acoustic parameters (for example, articulation rate, syllable duration, frequency of pauses; Ivanova et al., 2022) with healthy controls. Groups are formed based on performance on global cognitive screening tools and differences in acoustic features are typically found (for a systematic review see Martínez-Nicholás et al., 2021). Ivanova et al. (2022) pointed out that many acoustic parameters that identify AD are also distinctive in MCI and healthy motor speech abilities. For example, in their review, all groups were reported as having slower articulation rates and increased pauses (Ivanova et al., 2022). Similar results were identified by Meilán et al. (2020), who reported increasingly longer articulation times with severity of cognitive impairment in a passage reading task

Further evidence for the cognition-motor speech link comes from studies involving typical young adult speakers, as well as in other clinical populations, such as Parkinson's Disease (PD). For example, attention, working memory and executive functioning have been separately linked to characteristics of speech motor control in these groups (Bailey & Dromey, 2015; Doneva, 2020; Dromey & Benson, 2003; Dromey & Shim, 2008; Dromey & Simmons, 2019; Guo et al., 2017; Liu et al., 2019; Shen & Janse, 2020; Whitfield et al., 2021). Also, Smith's (1999) influential multifactorial model of stuttering proposes that cognitive, linguistic, and emotional factors contribute to the speech motor system in speakers who stutter. While Smith postulates that increased memory load impacts upon motor speech stability, a meta-analysis has conversely linked stuttering specifically to attentional capacity (Doneva, 2020). These results are not necessarily contradictory, as attention and memory are intimately related (Baddeley et al., 2020; Cowan, 2020). However, they demonstrate that studies considering just one cognitive domain may fail to capture the interplay of overlapping cognitive processes (Deary et al., 2006), and that there is therefore a need to gather evidence across a range of cognitive abilities when examining relationships with older adults' motor speech production.

Theoretically, the common cause hypothesis (Baltes & Lindenberger, 1997) could explain the potential relationship between cognition and motor speech production. This hypothesis proposes that one common factor, such as neurodegeneration, is responsible for age-related cognitive and sensory declines (Lindenberger & Baltes, 1994), resulting in increased interdependence between sensory and cognitive systems (Li & Lindenberger, 2002). Indeed, sensory functioning (visual/auditory acuity) predicts more of the variance in fluid cognitive abilities (reasoning, memory, spatial orientation, cognitive/perceptual speed) in older than in younger adults (Baltes & Lindenberger, 1997). Dual-task studies also provide evidence for interdependence between cognitive and sensorimotor abilities (Li et al., 2001b; Lindenberger et al., 2000), particularly when the secondary task is attention-demanding (Li & Lindenberger, 2002). From the perspective of Selection, Optimization, and Compensation (SOC) theory (Baltes et al., 2006), reduced cognitive resources mean that older adults may need to select where to allocate attentional resources, resulting in dual-task costs to one activity. While vision and hearing (and walking, to a lesser extent) have been investigated thoroughly in the context of a common cause (Li et al., 2001a; Lindenberger & Ghisletta, 2009; Wayne & Johnsrude, 2015), motor speech production – a sensorimotor process (Tremblay et al., 2016) – has been explored less, particularly in typical aging. Beyond a common factor at the neurological level (i.e. neurodegeneration), there may also be direct links between cognitive and motor speech variables at the information-processing level. Prominent candidates are information processing speed (Salthouse et al., 1996), working memory (Baddeley et al., 2012, 2020), and inhibition/interference (Campbell et al., 2020; Lustig et al., 2007).

1.5. Summary

In summary, on an empirical and theoretical basis, cognitive processes may be involved in motor speech production. However, there is no clear consensus on which, and to what extent, specific cognitive abilities could be involved in typical motor speech production. While it is agreed that there exist age-related changes to both cognition and motor speech abilities, the extent to which there are relationships between these two domains remains under-explored. Zraick et al. (2006) noted that the evidence for articulatory and phonatory changes in aging centres around underlying anatomy and physiology. Thus far, systematic reviews in the area have focused only on acoustic markers or intelligibility analysis of speech (de la Fuente Garcia et al., 2020; Martinez-Nicholas et al., 2021; Pommée et al., 2021; Tucker et al., 2021). The present systematic review addresses the potential impact of core cognitive abilities on motor speech production while considering articulatory and non-segmental features in both in healthy older adults and those with MCI, who have no known speech and/or language problems. The current research was aimed at gathering and synthesising relevant available quantitative evidence, to establish the relationships amongst cognitive and motor speech abilities within each of these two groups.

2. Methods

2.1. Transparency and openness

This systematic review followed guidelines from the Centre for Reviews and Dissemination for undertaking reviews in health care (The CRD, 2009). The protocol was pre-registered on PROSPERO (Central Registration Depository number: CRD42021235159) on 4th February 2021 (https://www.crd.york.ac.uk/PROSPERO/view/CRD42021235159).

2.2. Search strategy

A systematic search of four databases (PsycInfo, PubMed, Web of Science and the Cochrane Library) was initially conducted on 8th March 2021. The search was repeated on 5th August 2021, 21st June 2022, and most recently on 1st October 2024 to check for more recent publications. By necessity, searches maintained English language restrictions but were not restricted by date of publication. The full search term comprised the intersection between speech, cognition, and healthy and cognitively impaired older adults: [(speech production OR speech motor control OR motor speech OR articulat* OR speech fluency OR voice) AND (global cognit* OR cognit* function* OR cognit* performance OR executive function* OR process* speed OR attention* OR memory OR inhibit*) AND (older adult OR elder* OR ag?ing OR senior OR mild cognitive impairment OR MCI OR dementia OR Alzheimer)]. The search was supplemented by manually searching reference lists of included studies and related publications. Supplementary searches included extra terms related specifically to 'pausing' or 'speech rate' and identified comparison groups in a wider range of clinical studies, that is [(Parkinson's Disease) AND (control group OR age-matched controls)].

2.3. Inclusion and exclusion criteria

Our initial scoping searches returned few results when searching the basic terms of 'cognition', 'speech production', and 'older adults/age'. Therefore, we opted for broader inclusion criteria to capture as much relevant data on the topic as possible. Eligible studies contained quantitative behavioural data obtained from adults with an average age of 60 and above. Some cognitive abilities begin to decline from early adulthood (as early as the third decade of life), but declines become steeper and more noticeable within older age, and specifically after 60 years (Salthouse, 2009), which can therefore be considered a threshold age. Studies included cognitively healthy older adults and/or older adults with suspected or diagnosed MCI, with the latter group exhibiting more significant age-related decline. Studies that contained participants with speech and/or language disorders (e.g. apraxia of speech, aphasia) were excluded (e.g. Marangolo et al., 2013; Martins et al., 2009), unless there was a relevant, separable control group. Studies that recruited healthy or MCI groups as controls in clinical studies of patients with PD, AD, or any other clinical disorder, could be included, if the relationship between cognition and motor speech production had been measured behaviourally, and the data from the target population was separable. Similarly, older adults that acted as comparator groups in studies of young or middle-aged adults were also included, if relevant, separable data on older adults was available.

All forms of speaking task were eligible for inclusion, for example, syllable, word or sentence repetition tasks, oral reading tasks, monologue production or conversational tasks. To be as comprehensive as possible, we included a wide range of measures, specifically perceptual, acoustic or transcribed features such as articulation and/or speech rate, dysfluencies (pauses, repetitions, revisions) intelligibility analysis, articulatory-kinematic characteristics, formants or voice features. Studies should have contained at least one measure of cognitive functioning, such as accuracy, response times and/or processing/production rate, based on global cognitive functioning tasks (e.g. dementia screening tools), or measures of specific abilities such as attention, memory, or speed of processing. Given the interaction between cognition and language processing (Perlovsky & Sakai, 2014) language was included as a cognitive ability. Therefore, studies measuring cognitive-linguistic abilities (e.g. vocabulary, verbal fluency, naming, grammatical or syntactic complexity) could be included if they also contained a motor speech outcome and had measured the relationship between the two domains. Given our aim, studies that focused on language processing as an outcome (i.e. no motor speech outcomes; e.g. Biran et al., 2023) were excluded. Studies must have measured the relationship between cognition and motor speech production, for example using correlational analysis or by experimental manipulation. Studies containing only qualitative, or neuroimaging data were excluded. Clinical studies (other than in MCI) that contained age-matched controls were excluded if the relationship between cognition and motor speech production had not been analyzed separately in the controls.

2.4. Data screening and selection

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020; Page et al., 2021) statement was used to guide the process of study selection. The updated statement defines 'record' as the title and/or abstract of a report. 'Report' refers to the document containing, for instance, a journal article or conference abstract and a 'study' is the investigation involving participants, exposure, and outcomes (Page et al., 2021). Studies using the same dataset should be grouped (The CRD, 2009), however no included reports contained multiple studies, therefore, the term 'study' presently refers to individual journal articles. In two studies, it was unclear if the data had been re-analyzed (Kemper et al., 2005, 2011). Authors were contacted; however, no response was received. These studies are therefore tabulated separately.

The processes of data screening and extraction were guided by AMSTAR 2 (Assessing the Methodological Quality of Systematic Reviews; Shea et al., 2017). All records obtained from the searches were imported into EndNote 20 (The Endnote Team, 2013) and screened by the first reviewer (LM) according to the inclusion/exclusion criteria. Records were excluded if they were clearly unrelated to the topic or did not address at least two of the three main criteria. If the population was not specified in the abstract, the record was included for full-text screening. For the initial searches, a second independent reviewer (AKr) filtered 25% of the records, using the same criteria. According to AMSTAR 2, it is acceptable for the second reviewer to screen a proportion of the records for study inclusion. The two reviewers initially reached substantial agreement (McHugh, 2012), obtaining a Cohen's kappa (κ) of 0.63. Importantly, every record on which there was some disagreement was discussed by the two reviewers. A consensus procedure took place, where disagreements about record inclusion were resolved through the two reviewers independently reviewing the records in disagreement, while stating reasons for inclusion or exclusion. Any remaining records still in disagreement were resolved through discussion by the two reviewers with two experts in cognitive (LN) and speech sciences (AKu) available to help resolve disagreements. Full texts were screened by the first reviewer, with the second reviewer independently screening 25% of these. The two reviewers reached almost perfect agreement of $\kappa = 0.82$. To benefit accuracy further, two experts in cognitive and speech sciences (AKu, LN) then thoroughly checked the included articles for eligibility.

2.5. Data extraction

A data extraction form for quantitative data was developed according to protocols from the Cochrane Collaboration (EPOC, 2017) and was tailored to the review question. The form contained tables for extracting data related to study details (e.g. title, authors, date of publication), participant characteristics (e.g. total number, min-max and mean age, gender, education), methodology (e.g. aims, study design, tasks), outcome data (e.g. statistical analyses, results) and risk of bias/quality appraisal. Missing descriptive details (e.g. age range, gender) were recorded as 'not specified' and are reported in the primary synthesis of study characteristics table (Table 1). Missing information that could impact the outcome, such as failure to report inclusion criteria, was considered in the quality appraisal (Table 2). The first reviewer extracted relevant data for all included studies, with the second reviewer independently extracting data from 25% of the studies. Again, to ensure accuracy, the two experts in cognitive and speech sciences (AKu, LN) thoroughly checked the extracted data from the included studies.

2.6. Quality appraisal

The Mixed Methods Appraisal Tool (MMAT; Hong et al., 2018) was used to evaluate the quality of individual studies, including risk

Table 1
Characteristics and aims of studies included in the review, organized alphabetically by first author name.

Study	Total sample size (N)	Participant/ patient type included in study	Subgroup (hOA or MCI) included in review (n)	Age (yrs)		Gender (%)		Education (yrs)	Design	Aims of the study
				M (*SD*)	Min-Max	Male	Female	*M (SD)*		
Abur et al. (2021)	12	hOA	12 hOA	73.4 (0.3)	68 - 78	6 (50%)	6 (50%)	-	Cross-sectional, experimental	To evaluate the effects of cognitive load on the degree of autonomic arousal and vocal acoustics in a cohort of healthy older adults.
Bunton & Keintz (2008)	8	hOA PD	4 hOA	67.3 (2.4)	62 - 71	-	-	-	Cross-sectional, experimental	To compare speech intelligibility scores in single and dual task conditions for speakers with PD and an age-matched control group.
Collette et al. (1999)	40	hOA AD	20 hOA	71.75 (4.83)	-	3 (15%)	17 (85%)	-	Cross-sectional, correlational	To re-examine the nature of working memory deficits in a group of mild to moderate AD patients compared to healthy controls.
Crutch et al. (2013)	40	hOA PCA LPA	18 hOA	67.9 (5.4)	-	9 (50%)	9 (50%)	-	Cross-sectional, correlational	To examine and characterize the linguistic profile of Posterior Cortical Atrophy (PCA) by comparing with healthy controls and patients with Lopogenic/Phonological Aphasia (LPA).
de Looze et al. (2018)	70	hOA MCI AD	36 hOA 16 MCI	71.13 (5.83) 73.81 (6.96)	- -	19 (53%) 11 (69%)	17 (47%) 5 (31%)	13.72 (1.48) 13.43 (1.75)	Cross-sectional, correlational	1. To investigate whether speech characteristics reflect cognitive impairments including deficits in working memory and attention. 2. To investigate whether reading aloud may exhaust the limited cognitive resources of a reader, specifically working memory and attention. 3. To investigate whether speech timing and chunking lead to slower speech rates and more dysfluencies in participants with a higher level of cognitive impairment, and whether they may chunk their speech into a higher number of speech units and of smaller duration. 4. To test the effect of cognitive-linguistic demand (increased sentence length and syntactic complexity) on speech timing and chunking. 5. To explore the discriminative ability of temporal speech parameters for the detection of MCI and AD.
Dromey et al. (2010)	26	hOA PD YA	7 hOA	70.50 (11.90)	-	-	-	-	Cross-sectional, experimental	To provide detailed measures of both speech and postural performance to quantify the extent of bidirectional interference in people with PD relative to age-matched and younger control participants.
Foreman et al. (2013)	24	hOA PD YA	7 hOA	70.50 (11.90)	-	5 (71%)	2 (29%)	-	Cross-sectional, experimental	To examine the effects of age and PD on practice-based changes in concurrent postural task and speech motor task performance when compared to healthy age-matched and healthy young controls.
Fournet et al. (2021)	27	hOA	27 hOA	73.59 (8.49)	-	13 (48%)	14 (52%)	-	Cross-sectional, experimental	Experiment 3 investigated whether post-lexical processes recruit attentional resources in older adults. (Note, two additional experiments focused on young adults.)
Kemper et al. (2003)	150	hOA YA	75 hOA	73.0 (6.4)	70-80	-	-	-	Cross-sectional, experimental	To establish whether concurrent task demands have differential effects on young and older adults' speech.
Kemper et al. (2005)	48	hOA YA	24 hOA	74.80 (7.2)	70-80	-	-	-	Cross-sectional, experimental	To extend Kemper et al. (2003) by determining how increasing costs of walking will affect speech of younger and older adults.

(*continued on next page*)

Table 1 (*continued*)

Study	Total sample size (N)	Participant/ patient type included in study	Subgroup (hOA or MCI) included in review (n)	Age (yrs)		Gender (%)		Education (yrs)	Design	Aims of the study
				M (SD)	Min-Max	Male	Female	*M (SD)*		
Kemper et al. (2009)	80	hOA YA	40 hOA	74.30 (6.07)	65-85	-	-	17.1 (3.0)	Cross-sectional, experimental	To further investigate age-differences in dual task demands on language production using a digital version of the classic pursuit rotor tracking task.
Kemper et al. (2011)	80	hOA YA	40 hOA	74.30 (6.07)	65-85	-	-	17.1 (3.0)	Cross-sectional, experimental	To directly compare how varying task priorities affect young and older adults' language production using a dual-task procedure.
Kim et al. (2019)	73	hOA aMCI naMCI	21 hOA	71.90 (6.84)	-	3 (14%)	18 (86%)	8.5 (2.9)	Cross-sectional, correlational	1. To examine the differences in discourse ability in aMCI naMCI and HC groups. 2. To investigate cognitive functions associated with each measure of discourse in the two subgroups of MCI patients.
			30 aMCI	73.80 (6.41)	-	11 (37%)	19 (63%)	-		
			22 naMCI	70.09 (6.27)	-	6 (27%)	16 (73%)	-		
Lowit et al. (2006)	60	hOA hDEM AD PD	20 hOA	67.90 (5.96)	61-79	16 (80%)	4 (20%)	-	Cross-sectional, correlational	1. To investigate pausing and articulation in healthy and PD speakers with and without cognitive decline. 2. To assess the speaker's ability to modify their articulation rate from moderate to fast and slow conditions. 3. To identify potential predictors to explain participants speech performance.
			9 hDEM	80.56 (10.68)	62-99	4 (44%)	5 (56%)	-		
MacPherson (2019)	24	hOA YA	12 hOA	73.25 (3.42)	68-78	6 (50%)	6 (50%)	17.25 (2.14)	Cross-sectional, experimental	To determine the cognitive load imposed by a speech production task on the speech motor performance of healthy older and younger adults.
Morris (1987)	42	hOA AD	21 hOA	77.0 (7.3)	-	4 (19%)	17 (81%)	9.9 (1.8)	Cross-sectional, correlational	To investigate the relationship between articulation rate and memory span in AD patients and healthy controls.
Pohl et al. (2011)	36	hOA Stroke	12 hOA	72.7 (8.0)	-	6 (50%)	6 (50%)	17.1 (1.6)	Cross-sectional, experimental	To examine how older adults with and without stroke meet the demands of walking while conversationally speaking.
Thies et al (2020)	38	hOA PD	19 hOA	65.4 (9.3)	50-79	13 (68%)	6 (32%)	-	Cross-sectional, correlational	1. To investigate the nature of prominence production by measuring phonetic continuous variables in speakers with PD. 2. To investigate the relationship between prosodic prominence and cognitive abilities.
Walsh & Smith (2011)	32	hOA PD	16 hOA	73 (3.0)	63-80	11 (69%)	5 (31%)	15.9 12-20	Cross-sectional, experimental	To perform multilevel assessments of speech production and comprehension abilities in individuals with PD and age-matched controls.
Whitfield & Goberman (2017)	45	hOA PD YA	14 hOA	64.93	48-81	5 (36%)	9 (64%)	-	Cross-sectional, experimental	To further investigate the effect of normal aging and PD on speech motor learning.
Whitfield et al. (2019)	23	hOA PD	11 hOA	67 (6.34)	54-75	2 (18%)	9 (82%)	-	Cross-sectional, experimental	To quantify baseline dual-task interference associated with concurrent performance of a low-demand manual task and connected speech tasks in individuals with and without PD.
Yu et al. (2014)	214	hOA	214 hOA	>75	-	72 (34%)	142 (66%)	-	Data were taken from a 4-year longitudinal study	To assess the effect of neurophysiological changes associated with dementia on motor timing and coordination, and therefore articulatory control and kinematics.

Note. Alzheimer's Disease (AD), Amnestic MCI (aMCI), Early Onset Dementia (hDEM), Healthy Older Adults (hOA), Lopogenic/Phonological Aphasia (LPA), Mild Cognitive Impairment (MCI), Non-amnestic MCI (naMCI), Parkinson's Disease (PD), Posterior Cortical Atrophy (PCA), Young Adults (YA).

Table 2
Assessment of research quality using the Mixed Methods Appraisal Tool (MMAT, Version 18; Hong et al., 2018).

Study		Quantitative non-randomized studies				
Authors	Date	3.1 Are the participants representative of the target population?	3.2 Are measurements appropriate regarding both the outcome and intervention (or exposure)?	3.3 Are there complete outcome data?	3.4 Are the confounders accounted for in the design and analysis?	3.5 During the study period, is the intervention administered (or exposure occurred) as intended?
Abur et al.	2021	No	Yes	Yes	Yes	Yes
Bunton & Keintz	2008	No	Yes	No	Yes	Yes
Collette et al. *	1999	Yes	Yes	Yes	Yes	Yes
Crutch et al.	2013	No	Yes	Yes	Yes	Yes
de Looze et al. *	2018	Yes	Yes	Yes	Yes	Yes
Dromey et al.	2010	No	Yes	Yes	No	Yes
Foreman et al.	2013	No	Yes	Yes	No	No
Fournet et al.	2021	No	Yes	Yes	No	Yes
Kemper et al.	2003	Yes	Yes	No	No	Yes
Kemper et al.	2005	Yes	Yes	No	No	Can't Tell
Kemper et al.	2009	Yes	Yes	Yes	No	Yes
Kemper et al.	2011	Yes	Yes	Yes	Yes	Can't Tell
Kim et al. *	2019	Yes	Yes	Yes	Yes	Yes
Lowit et al.	2006	Yes	Yes	Yes	No	Yes
MacPherson	2018	No	Yes	Yes	Yes	Yes
Morris	1987	No	Yes	Yes	No	Yes
Pohl et al.	2011	Yes	Yes	Yes	No	Yes
Thies et al.	2020	No	Yes	Yes	Yes	Yes
Walsh & Smith *	2011	Yes	Yes	Yes	Yes	Yes
Whitfield & Goberman	2017	No	Yes	Yes	Yes	Yes
Whitfield et al.	2019	No	Yes	Yes	Yes	Yes
Yu, et al. *	2014	Yes	Yes	Yes	Yes	Yes

Note. The Qualitative, Quantitative randomized controlled trials, Quantitative descriptive, and Mixed methods categories were not relevant for the present review;
[*] studies that met all criteria.

Table 3
Summary of relationships between motor speech subprocesses and cognitive factors.

	Participants	Speech execution		Cognitive Factors Assessed						Findings
				Fluid abilities					Crystallized abilities	
		non-segmental	articulation	Global cognition	Speed of processing	Attention/ Executive functioning	Working memory	Long-term memory	Verbal knowledge	
Abur et al. (2021)	Healthy	Y	N	N	N	Y	N	N	N	No relationship between cognition and acoustic voice measures (e.g. cepstral peak prominence, fundamental frequency, sound pressure level).
Bunton & Keintz (2008)	Healthy	N	Y	N	N	Y	N	N	N	Intelligibility ratings did not differ from single to dual task conditions.
Collette et al. (1999)	Healthy	N	Y	N	Y	N	Y	N	N	Significant negative correlation only between speed of processing and articulation rate.
Crutch et al. (2013)	Healthy	N	Y	N	N	Y	N	N	Y	No significant relationship between executive functioning and articulation
De Looze et al. (2018)	Healthy & MCI	N	Y	N	N	Y	Y	N	Y	In healthy older adults a significant positive relationship between verbal knowledge and speech fluency. In MCI a significant positive relationship between attention/working memory and speech fluency
Dromey et al. (2010)	Healthy	N	Y	N	N	Y	N	N	N	Dividing attention between a speech and postural task resulted in significant dual task costs to the “rise to toes” task only.
Foreman et al. (2013)	Healthy	N	Y	N	N	Y	N	Y	N	Changes from single to dual task conditions not reported. No significant effect of practice (learning) on speech or postural measures.
Fournet et al. (2021)	Healthy	N	Y	N	Y	Y	N	N	N	Articulation was significantly faster under single task conditions, only when the secondary task involved executive processes as opposed to processing speed.
Kemper et al. (2003)	Healthy	N	Y	N	N	Y	N	N	N	Dividing attention significantly reduced the efficiency of articulatory characteristics.
Kemper et al. (2005)	Healthy	N	Y	N	N	Y	N	N	N	Dividing attention significantly reduced the efficiency of articulatory characteristics.
Kemper et al. (2009)	Healthy	N	Y	N	Y	Y	Y	N	N	Speech rate significantly decreased from single to dual-task conditions. Processing speed was significantly correlated with speech rate in single and dual-task conditions.
Kemper et al. (2011)	Healthy	N	Y	N	Y	Y	Y	N	N	Significant dual-task costs to speech rate, but only under conditions where the concurrent task was emphasized. There were significant associations only between speed of processing and speech rate in all conditions.
Kim et al. (2019)	aMCI and naMCI	N	Y	N	N	Y	Y	Y	Y	Significant negative relationships between long-term visuospatial memory and pausing, and between executive functioning and speech rate.

(*continued on next page*)

Table 3 (*continued*)

	Participants	Speech execution		Cognitive Factors Assessed: Fluid abilities					Crystallized abilities	Findings
		non-segmental	articulation	Global cognition	Speed of processing	Attention/ Executive functioning	Working memory	Long-term memory	Verbal knowledge	
Lowit et al. (2006)	Healthy and MCI (early onset dementia)	N	Y	Y	N	N	N	N	N	Significant positive correlation between global cognition and ability to speed up articulation in healthy older adults. No significant relationship between global cognition and articulation rate or rate change (normal to slow). Significant positive correlation between global cognition and articulation rate for reading passages in MCI. No significant correlations between global cognition and articulation rate for sentences.
MacPherson (2019)	Healthy	N	Y	N	N	Y	N	N	N	Speaking in high cognitive load conditions significantly impacted articulatory kinematic characteristics, compared to low cognitive load conditions. Production accuracy was also poorer in high cognitive load conditions.
Morris (1987)	Healthy	N	Y	N	N	N	Y	N	N	Significant positive correlations between working memory and articulation rate for words and digits.
Pohl et al. (2011)	Healthy	N	Y	N	N	Y	N	N	N	No significant differences in speech rate when talking while walking. Significant difference in steps per minute in the walking and talking condition.
Thies et al. (2020)	Healthy	Y	Y	N	Y	Y	Y	N	N	No significant associations between motor speech markers and cognitive factors in healthy older adults.
Walsh & Smith (2011)	Healthy	N	Y	N	N	N	N	N	Y	Increasing linguistic complexity significantly reduced articulatory precision.
Whitfield & Goberman (2017)	Healthy	N	Y	N	N	Y	N	N	N	There was a significant decrease in accuracy, and a significant increase in duration from single to dual-task conditions.
Whitfield et al. (2019)	Healthy	Y	Y	N	N	Y	N	N	N	No significant changes from single to dual task conditions for any of the speech outcomes.
Yu et al. (2014)	Healthy	Y	Y	N	N	Y	N	N	N	Executive abilities were significantly associated with articulation and respiration/phonation features.

Note. aMCI (amnestic MCI); naMCI (non-amnestic MCI).

of bias. The MMAT allows appraisal of a variety of specific study designs including non-randomized quantitative studies, the category assigned to all included studies. Each study was evaluated on the five criteria of representativeness, measurements, complete data, confounding and design (Table 2). Note, according to the MMAT, indicators of representativeness include clear descriptions of the target population and sample, and any attempts to achieve a representative sample (Hong et al., 2018). For the criterion of representativeness, and in the context of each study's aims, we considered age ranges, sample size, and whether inclusion/exclusion criteria were clearly adhered to. Regarding sample size, where possible, using the information provided in each study, we used G*Power (Faul et al., 2007) to calculate the required sample size for detecting a large effect using the specified core analyses, with power set to the minimum 0.80 and alpha at 0.05. Confounders are factors that can impact a study's outcomes which should be accounted for in the design and/or analysis (Hong et al., 2018). Confounders most relevant to the current work pertain to whether any cognitive screening was carried out in participants prior to inclusion in the study. Other confounders specific to a particular study's outcomes were also noted (Table 1).

If a study clearly met a specific criterion, it was given a 'yes' answer. If studies did not meet the criterion, or authors did not provide adequate detail or description against the criterion, they were marked as 'no'. In the latter case, further details were sought from associated publications and/or the authors were contacted for clarity. If the details could not be accessed, the criterion was marked as 'can't tell'. Scoring each study out of a possible five is discouraged by Hong et al. (2018), due to lack of informativeness in itself. Therefore, the responses for each criterion are presented in Table 2, and Supplementary Table 1 outlines the rationale for 'no' and 'can't tell' answers. The first reviewer conducted quality analyses for all included studies, with the second reviewer independently evaluating 25% of the studies. The two reviewers initially reached agreement of $\kappa = 0.54$, indicating moderate agreement about which studies met all MMAT criteria. The quality assessment of the included studies was then also reviewed by the two subject experts (AKu, LN). Disagreements were resolved through discussions until consensus was achieved.

2.7. Data synthesis

Upon pre-registering this review, it was predicted that a meta-analysis would not be possible due to heterogeneity of measures across studies, a problem also noted in similar reviews (e.g. Tucker et al., 2021). Results are therefore reported via a narrative synthesis. Following The CRD (2009) guidelines, a preliminary synthesis of study characteristics is presented in Table 1. The key findings from each study are presented in a summary table (Table 3). All included studies are listed alphabetically by first author surname and the observed relationships between cognitive factors and measures of articulation (e.g. articulation rate, speech rate and/or non-segmental features (e.g. fundamental frequency (F_0), pauses, sound pressure level). Articulatory outcomes are predominantly durational in nature (e.g. articulation rate/speech rate; Waito et al., 2021). Kinematic characteristics are also classified as representing articulation (Kuruvilla-Dugdale et al., 2020). Supplementary Table 2 contains the raw data extracted from each study, providing a more detailed description of the measures and outcomes. Given the heterogeneity in trajectories of age-related change across cognitive abilities (e.g. Salthouse, 2019), in the text, the findings are grouped by cognitive ability. Within cognitive domains, the relationships with motor speech findings are discussed and organized by participant group (healthy followed by MCI). This allowed exploration of

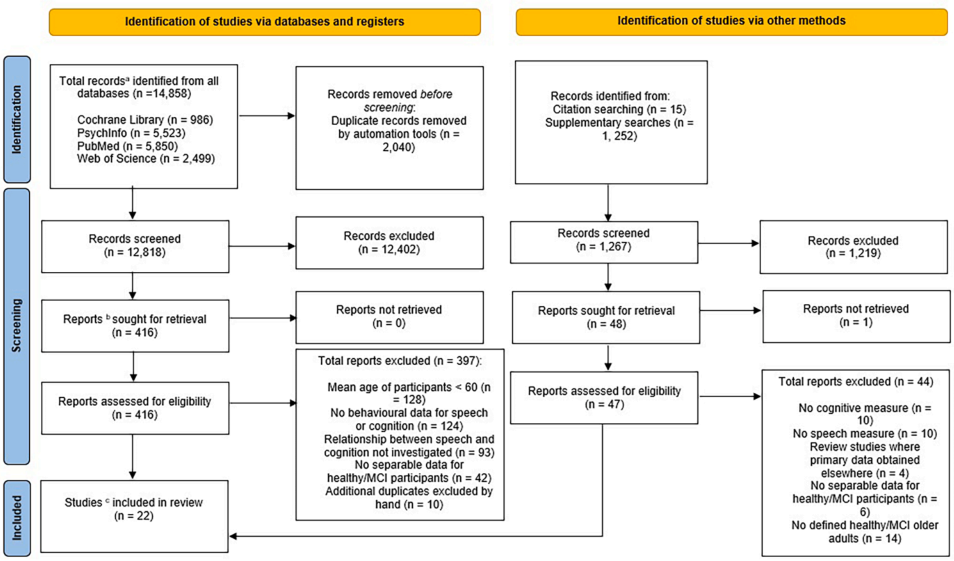

Fig. 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses, 2020) flow diagram depicting searching and filtering process.
Note. [a] Record: title, abstract (or both) of a report indexed in a database or website; [b] Report: A document supplying information about a study (e.g., journal article, preprint, thesis, conference abstract); [c] Study: an investigation (e.g., clinical trial) that includes defined groups of participants and intervention/exposure (Page et al., 2021).

relationships within and between studies, including identifying possible heterogeneous outcomes. The robustness of the synthesis was assessed by considering the weight of evidence in terms of number of individual studies in which there was a significant effect in relation to a specific outcome, total number of participants, and quality of evidence.

3. Results

In total, 14,858 records were identified from the database searches. After removing duplicates, 12,818 records were filtered based on titles and abstracts. From this, 463 reports (i.e. 416 + an additional 47 identified via other methods) were selected for full-text screening. In total, 22 studies, published between 1987 and 2021, were deemed eligible and included in the review. A PRISMA flow diagram (Page et al., 2021) documents the process of study inclusion and reasons for exclusion (Fig. 1). For example, while some studies appeared to include a motor speech measure (e.g. pause duration), the aims were focused on language production and these studies were therefore excluded (e.g. Dodge et al., 2015; Kobayashi et al., 2019; Malcorra et al., 2021; Mueller et al., 2018; Pistono et al., 2016, 2019; Rodríguez-Aranda & Jakobsen, 2011).

3.1. Study characteristics

The total number of older adults included in this review was 747 (332 females, 44.44%; 225 males, 31.12%; remainder not reported), with 670 healthy older adults, and 77 with diagnosed or suspected MCI. The average age of the healthy participants ranged from 64.9 to 74.8 years, and for MCI participants this was 70.1 to 80.6 years. Study designs were predominantly cross-sectional, where healthy older adults were recruited as age-matched controls in clinical studies or as comparators in studies including younger adults (Table 1). Only two studies exclusively recruited healthy older adults (Abur et al., 2021; Yu et al., 2014).

3.2. Quality evaluation

Out of 22 included studies, five met all five criteria for their study type (Table 2), indicating the highest quality research, according to the MMAT (Hong et al., 2018). For studies not meeting all criteria, most commonly this was due to lack of representativeness. One issue was sample size, with many studies not meeting even the minimum required sample size for detecting a large effect size using the type of statistical analysis conducted (Supplementary Table 1). It is important to acknowledge that, in some cases, the number of healthy older adults were recruited to match the number of patients recruited in clinically-focused studies. It is understandably more challenging to recruit from clinical populations. Nevertheless, this finding highlights a lack of sufficiently powered research involving healthy aging. Studies that did not account for confounders in the design and/or analysis primarily failed to administer cognitive screening instruments (e.g. Abur et al., 2021; Dromey et al., 2010; Foreman et al., 2013; Kemper et al., 2009, 2011). In addition, although the average age of participants in all samples was 60 or above, some studies recruited participants younger than 60 (Dromey et al., 2010; Foreman et al., 2013; Thies et al., 2020; Whitfield & Goberman, 2017; Whitfield et al., 2019) which may limit the generalizability of the results to the older adult population. This has been considered in the quality evaluation where appropriate (Table 2). In four studies, there were inconsistencies with reporting results, including omission of *p*-values (Kemper et al., 2003, 2005, 2009, 2011). Finally, in one study, descriptions of the aims, methods and procedures were inadequate for replication (Morris, 1987).

3.3. Cognitive measures and their impact on motor speech production

The reviewed studies varied with respect to the cognitive and motor speech measures that were included. Motor speech measures could be grouped into articulation rate, speech/speaking rate, pausing, segment duration, articulatory control, and articulatory accuracy. These will now be discussed in relation to the cognitive domains with which they were examined.

3.3.1. Global cognitive functioning

Out of the 22 included studies, one addressed global or generalized cognition in healthy older adults and in MCI. Healthy speakers with greater scores on the Addenbrooke's Cognitive Examination (ACE; Mathuranath et al., 2000) were more able to control articulation by increasing articulation rate from habitual to fast conditions (Lowit et al., 2006). In addition, in the MCI group, superior cognitive score was significantly associated with faster articulation rates (Lowit et al., 2006) in a reading task. Therefore, global cognition may predict articulatory characteristics including faster articulation rates in both healthy older adults and in MCI, as well as the ability to control these. However, to be able to make confident conclusions, more research is required that explores relationships between global cognition and speech motor subprocesses in healthy older adults and in those with MCI (Table 3).

3.3.2. Speed of processing

In three of four studies of healthy older adults, significant relationships between speed of processing and motor speech execution were reported (Table 3). A variety of processing speed measures were used across studies, from relatively basic response time measures such as letter comparison (Collette et al., 1999) to more complex digit-symbol substitution (Kemper et al., 2009, 2011; see Supplementary Table 2). As expected, faster processing speed was associated with faster speech rate in two studies implementing an expository speech task (Kemper et al., 2009, 2011). However, due to the naturalistic conversational task, and due to measuring words per minute which contains pauses, it is not possible to say whether processing speed is associated with speech rate over and above language and cognitive (memory) processing and/or speech motor planning. However, Collette et al. (1999) reported similar results for a non-word repetition task which did not require any language processing, thus lending support to the argument that processing speed can indeed impact articulation rate. One further study investigating processing speed in conjunction with speech parameters was by Thies et al. (2020), who reported on articulation and phonatory parameters in a contrastive stress task. They measured processing speed using the Trail Making Test-A (TMT-A), a relatively low-level measure of processing speed requiring making a trail between connecting items (numbers; Salthouse, 2011). Thies et al. found no significant associations between TMT-A performance and the acoustic markers. Given the differences in task as well as motor speech outcome measures, these results are not necessarily contradictory to the previous studies. Instead, they serve to highlight the fact that cognitive processes might not impact on all motor speech processes in the same way. Finally, the relationship between speed of processing and motor speech production in MCI was not reported in any study.

Evidence on the relationship between processing speed and motor speech production is therefore limited by confounding from long-term memory required for monologues about past events (Kemper et al., 2009, 2011) as well as the language processing element involved in such tasks. As mentioned earlier, the data in Kemper et al. (2009, 2011) may also have been re-analyzed, reducing the overall number of participants and, thus, the strength of any conclusion based on the results here. However, it is worthwhile highlighting the more convincing design used by Collette et al. (1999). The increased demands involved in articulating non-words, coupled with a sensitive measure of articulation rate (syllables per second), showed a significant negative relationship with processing speed performance. This suggests that better processing speed may be associated with faster articulation in healthy older adults.

3.3.3. Attention/executive function

Most of the identified research examined the relationship between attention/executive functioning and motor speech subprocesses across 18 studies (Table 3), revealing mixed evidence. Of 11 studies incorporating a dual-task paradigm, six reported significant declines in articulation from single to dual-task conditions, including reduced speech rate (Kemper et al., 2003, 2005, 2009, 2011), word and syllable rate (Fournet et al., 2021), syllable accuracy, and sequence duration (Whitfield & Goberman, 2017). In these studies, the secondary tasks included walking, ignoring speech or noise, digital tracking and non-verbal cognitive or motor tasks.

A further five studies reported no significant changes to motor speech characteristics under dual-task conditions when the secondary task involved a 'rise to toes' task (Dromey et al., 2010; Foreman et al., 2013), oscillatory drawing (Whitfield et al., 2019), or screwing a nut on a bolt (Bunton & Keintz, 2008). Under dual-task conditions, no significant changes were found to acoustic or perceptual variables including speech rate, F_0, and intelligibility. The effect of dividing attention on speech may therefore depend on the complexity of the secondary task, whereby speech execution is unaffected until a certain threshold is reached and dividing attention across two tasks becomes more difficult. Pohl et al. (2011) reported no significant dual-task costs to speech rate despite administering a concurrent walking task. This may have been because older adults reduced their walking speed to maintain speech rate, showing that attentional resources were allocated differently depending on task priorities. It should be noted however that the five studies reporting a non-significant effect were all rated as poorer quality due to sample age ranges, sample size and lack of cognitive screening.

More convincing evidence comes from studies investigating higher-order executive processes and articulation where generally higher quality methods were displayed. For example, Fournet et al. (2021) measured word and syllable rate while participants recited the days of the week, a relatively automatic speech task minimizing the need for language or phonological planning. Participants performed a secondary non-verbal cognitive task while reciting the days of the week under two conditions varying in cognitive load. The 'Go' condition measured processing speed (i.e. respond each time a circle appears) and the 'Go/No-Go' condition required inhibition on some trials (i.e. respond to 'x' but not to '+'). Articulation was faster in the single speaking condition compared to the dual-task condition, but only when the secondary task was the more complex Go/No-Go task (i.e. articulation rate slowed under dual-task conditions). When the concurrent task was the simpler Go task, there were no changes to articulation rates. This provides support for a baseline level of dividing attention across tasks that allows participants to monitor speech successfully while completing a concurrent task. Conversely, articulation rate slows only under more cognitively challenging conditions that require both low-level attentional and higher-level executive abilities (e.g. inhibition or switching). However, this should be interpreted with caution due to the methodological quality of some studies (Table 2). Furthermore, it is unlikely that dual-task costs to speech can be wholly explained by reduced attentional resources due to aging, and it is more likely that additional cognitive and/or motor processes are involved.

Of four studies that directly examined the role of inhibition in speech, only one reported that increasing the cognitive load from congruent to incongruent Stroop (1935) conditions negatively impacted speech execution. MacPherson (2019) investigated articulation and speech motor control through the kinematic characteristics of lip aperture variability and movement duration. Articulation became more variable, suggesting poorer motor control, as the processing load increased during incongruent Stroop conditions. Moreover, while a similar relationship was observed in younger adults, the effect was greatest for the older adults who differed from younger adults on the kinematic measures, suggesting that age-related declines in inhibitory functioning could explain articulatory changes. Importantly, Abur et al. (2021) administered an identical Stroop paradigm and did not find significant changes to acoustic measures of non-segmental features (e.g. F_0, sound pressure level; Abur et al., 2021) under high cognitive load conditions. These experimental findings suggest that inhibition is involved in articulation but not the non-segmental aspects. Two further studies investigated the relationship between inhibition and speech rate (words per minute) using correlations and reported no significant relationships (Kemper et al., 2009, 2011).

In two of three studies investigating executive functioning using verbal fluency tasks (Amunts et al., 2021), one revealed a significant relationship with articulation (Yu et al., 2014). In this study, better 'animal fluency' was associated with faster speech rate, whereas no significant relationship was reported by Crutch et al. (2013). Although both elicited conversational speech, Yu et al. (2014)

measured phonemes per second excluding pauses, whereas Crutch et al. (2013) measured words per minute including pauses, which could explain the inconsistent results. Finally, Thies et al. (2020) reported no significant relationships between attentional control or set-shifting and duration, loudness or pitch of syllables during a stress production task. Taken together, there are some mixed outcomes regarding the relationship between attention/executive functioning and motor speech production, which could be explained by differences in tasks and outcome measures. Still, it is possible that older adults' articulatory ability is disproportionately affected due to age-related cognitive decline, and perhaps even specifically because of executive functioning.

In two studies involving participants with MCI, poorer executive abilities were associated with slower and more dysfluent speech, which could be attributed to speech planning (de Looze et al., 2018) and/or articulation (Kim et al., 2019). However, it is possible that some of these relationships were confounded by the influence of memory processes, as de Looze et al. (2018) included digit span tasks - a measure of working memory - in their composite measure of attention. In the study by Kim et al. (2019), a significant negative relationship showed that longer times to complete a colour word Stroop (1935) task was associated with slower speech rate in amnestic MCI (aMCI) patients with a dominant memory impairment. Longer times to complete the task could therefore be attributed to forgetting rather than inhibitory/executive functioning. Indeed, there was no relationship between Stroop accuracy and speech rate and no significant relationships found in non-amnestic MCI (naMCI) patients with dominant impairments in other cognitive domains (e.g. visuospatial abilities).

Most of the identified evidence in this review has investigated divided attention or executive functioning and their relationships with motor speech subprocesses, particularly articulation, in healthy and MCI participants. Within the significant findings, those that measure executive abilities and articulation are the most convincing as they contain well-designed studies, particularly in terms of measurements/outcomes and cognitive screening (Fournet et al., 2021; Kim et al., 2019; MacPherson, 2019; Yu et al., 2014). This reduces confounding and suggests a possible role for executive functioning in articulation. This however requires further replication with larger samples and coherence across the speech outcomes. In MCI, more valid measures of attention and consideration of subgroups of MCI patients are required.

3.3.4. Working memory

In six studies of healthy older adults, the relationship between short-term/working memory and motor speech production was assessed (Table 3). In three studies, the potential relationship between working memory span and articulation was investigated. In one study, larger capacity (span) was related to faster articulation rates (Morris, 1987) when measured using word reading and digit reading tasks. However, the small samples size and poor measure of articulation rate limit the accuracy of this finding. For example, timing the duration of the speech tasks (Morris, 1987) is less sensitive than measuring syllables per second (Collette et al., 1999). In four remaining studies, no significant relationships were reported with articulation rate, speech rate (Collette et al., 1999; Kemper et al., 2009, 2011) or acoustic measures including vowel formants, pitch, loudness, and syllable durations (Thies et al., 2020) in a stress task.

In MCI, the relationship between working memory and speech fluency was investigated in one study, and a significant association was observed (de Looze et al., 2018). In this study, speech fluency was likely to reflect speech planning because the speech task was manipulated by increasing the sequential complexity of the read sentences. However, the cognitive measure was a composite, comprising attention and working memory subscales, based on neuropsychological test performance. Therefore, it is unclear whether working memory in particular influences speech planning in MCI.

The evidence suggests that working memory span may be related to speech rate due to articulatory rehearsal in the phonological loop (e.g. Baddeley, 2012) representing language/phonological planning. However, further research is required, including larger samples and more sensitive measures of articulation rate.

3.3.5. Long-term memory

No studies investigated the relationship between long-term memory (LTM) and articulation in healthy older adults. In MCI, one study found that better delayed recall was associated with fewer pauses in non-amnestic MCI patients without a dominant memory impairment (naMCI; Kim et al., 2019). This study met our eligibility criteria because of their inclusion of additional speech measures such as speech rate. These results show that there is a gap in the literature addressing potential relationships amongst long-term memory and motor speech subprocesses in healthy older adults and in MCI.

3.3.6. Verbal knowledge/ability

Two studies looked at the relationship between verbal ability and motor speech production in healthy older adults (Table 3). De Looze et al. (2018) found that higher scores on a language composite predicted more fluent speech, measured by fewer speech chunks and pauses when reading sentences of increasing length and complexity. In one additional study (Walsh & Smith, 2011), repeating increasingly long and complex sentences increased lip aperture variability, a measure of speech stability and articulation, whereas production accuracy (measured by pauses and dysfluencies) was not affected. This again points to the conclusion that increased processing load affects older adults' articulation.

De Looze et al. (2018) also included a group of MCI patients. No significant correlations were found between the language composite and any motor speech variables in participants with MCI. This study allows direct comparison of healthy older adults and older adults with MCI, showing that crystallized verbal knowledge (Salthouse, 2012) or greater cognitive reserve (see Cabeza et al., 2018) in healthy aging may influence motor speech production, whereas in MCI there was no such relationship.

4. Discussion

Previous research suggests that cognition might explain some age-related differences between young and older adults' motor speech abilities that are not accounted for by physiological factors (e.g. Bilodeau-Mercure & Tremblay, 2016; Mortensen et al., 2006; Sadagopan & Smith, 2013; van Brenk et al., 2014). When performing speech tasks, older and younger adults show differences in speech planning (Tremblay et al., 2019a) and execution of both articulatory and non-segmental features (Karlsson & Hartelius, 2021). However, the link between cognition and motor speech subprocesses is currently unclear (e.g. Guenther & Vladusich, 2012; Levelt et al., 1999; Smith, 1999), with cognitive explanations being limited to explaining language production deficits. This systematic review collected, evaluated, and synthesized existing evidence on the potential relationship between cognitive and motor speech functioning in older adults. Data were gathered from 22 studies including cognitively healthy older adults and/or those with MCI. Some possible relationships between cognition and motor speech production in both healthy and MCI populations were identified, highlighting an important need for further research in this area.

This systematic review shows that, in healthy older adults, a range of cognitive abilities are associated with articulatory characteristics. Speech and articulation rate features were the most extensively investigated parameters in this relationship. Faster articulation rate was associated with better global cognitive functioning (Lowit et al., 2006), speed of processing (Collette et al., 1999), attention/executive abilities (Fournet et al., 2021; Yu et al., 2014) and working memory (Morris, 1987). Faster speech rate was also associated with faster speed of processing and better attention/executive abilities (Kemper et al., 2003, 2005, 2009, 2011). In addition, a number of other speech parameters such as pause production and segmental articulation/variability showed significant relationships with cognitive performance (de Looze et al., 2018; MacPherson, 2019; Walsh & Smith, 2011; Whitfield & Goberman, 2017). On the other hand, we did not identify any studies that reported a significant relationship between cognitive functioning and phonatory characteristics. However, this could be due to the paucity of research in this area, rather than the absence of such a relationship. Our review has not only succeeded in highlighting which aspects of motor speech production might be linked to cognitive ability, but also the specific cognitive skills involved. In addition to the early evidence from Smith (1999) pointing towards the involvement of memory load in articulation, our review has identified global cognition, speed of processing, attention/executive abilities, working memory and verbal knowledge/ability as also potentially playing specific roles.

The evidence reported here suggests that increased cognitive processing load negatively impacts aspects of motor speech production. Rather than memory load being the key component (Smith, 1999), the evidence was weighted towards a relationship between attentional resources ('executive functioning') and a variety of speech outcomes in healthy older adults, with approximately 80% of the included papers having measured this relationship. Studies implementing a relatively robust design reported that articulation rate (Yu et al., 2014), articulatory accuracy (Fournet et al., 2021) and speech kinematics (MacPherson, 2019; Walsh & Smith, 2011) were negatively impacted, particularly during high levels of cognitive demand. This mirrors the wider literature on the effects of attention on speech kinematics and speech motor control in young adults (Dromey & Benson, 2003; Dromey & Shim, 2008; Whitfield et al., 2021). It is also in line with a meta-analysis by Doneva (2020), who reported a link between attentional capacity and stuttering. However, just over half of the articles included in this review that assessed this relationship in healthy older adults reported a significant effect of, or relationship between, attention/executive abilities and motor speech. One explanation is that the overall body of work was limited by poorly controlled studies, small sample sizes, and lack of sensitivity in the measurements. Alternatively, the mixed findings could reflect heterogeneity in older adults' abilities. Doneva (2020) reports that the relationship between attention and stuttering was present only in a subgroup of people who stutter, indicating that it is unlikely for any effect to be present across all individuals in a target population. In the current research, the only demographic data considered, at times, were gender and years of education, and these variables were most frequently reported descriptively. Future researchers are encouraged to gather other potentially relevant demographic and health information. Examples include gathering data on dentition, pre-morbid intelligence, socioeconomic status, mental health status (such as mood/depression), hearing loss (particularly common in older age), and/or factors that may have a protective effect on aging speakers (e.g., linguistic profile, such as bilingualism, and musical ability), and to consider incorporating these variables into their analyses. This could help improve research quality by minimizing the impact of potentially confounding factors, ultimately resulting in more accurate conclusions.

One further interpretation is that speech production in older adults may be affected only when cognitive load reaches a threshold. This is in line with previous behavioural evidence showing differences in speech motor control accuracy in young and older adults, only at high levels of complexity in the speech task (Tremblay et al., 207). Selection, Optimization, and Compensation (SOC) theory (Baltes et al., 2006) proposes that age-related cognitive decline results in selecting where to allocate a larger share of attentional resources (e.g. Lindenberger et al., 2000). There could therefore be a lower threshold of dividing attention across two tasks where older adults are able to successfully monitor speech production using top-down processes, for example, when both tasks are being carried out within the individual's capacity for each task (e.g. Logie, 2011, 2023).

The findings also suggest that cognitive abilities may interact differently with the non-segmental features versus articulation. In terms of articulation, some measures such as the kinematic data (e.g. lip aperture variability index) and articulation rate measures might be more likely to capture changes than other outcome measures included in this review (e.g. words per minute, intelligibility analysis). The latter may either be insufficiently sensitive or may involve issues related to language processing. As such, these motor speech data in particular, coupled with the strongest cognitive data, suggest that executive abilities could be specifically involved in articulation, possibly in the form of speech monitoring (Postma, 2000). Barker et al. (2020) identifies executive functioning as a cognitive ability important for propositional, or everyday-like, language production. This review reveals that attention/executive functioning may be especially important in speech production, because it is additionally involved in articulation.

Interestingly, there was limited evidence suggesting a potential relationship between cognitive factors and non-segmental features in older adults. Just one out of four included studies reported a significant relationship between these aspects, specifically pausing behaviour (Yu et al., 2014). However, it should be noted that this study used free speech tasks, meaning this relationship may not actually reflect respiratory or phonatory features, but could instead be due to higher language processing such as utterance planning. Therefore, it is possible that cognitive factors may be related to articulation but not non-segmental features. From a theoretical perspective, the laryngeal DIVA model (LaDIVA; Weerathunge et al., 2022a), for the first time, acknowledges that the laryngeal and articulatory subsystems are not necessarily associated (Weerathunge et al., 2022b), suggesting that other processes, such as cognition, could interact differently with each subsystem. Our findings provide preliminary evidence that cognition could be involved in monitoring somatosensory feedback for articulation, and that age-related cognitive decline reduces the efficiency of this process. As it currently stands, there is not enough evidence to say whether cognition may or may not play a role in the production of non-segmental features, and this should be investigated in future research.

Although the current review focuses on relationships within older adults, it is notable that MacPherson (2019) included younger adults in their analysis. Both young and older adults showed increased variability in articulatory coordination and speech movement duration in high cognitive load conditions. However, the magnitude of the effect was greater for the older adults. In addition, sentence production accuracy was reduced under high cognitive load conditions only for the older adults. This suggests that speech execution in older adults may be disproportionately affected due to cognitive change. Further empirical research and theoretical development is required incorporating the role of cognition in both young and older adults to better understand speech motor control changes potentially due to cognitive aging.

One study (de Looze et al., 2018) was considered as having potentially measured the relationship between cognition and speech planning due to investigating the effect of manipulating sentence length and complexity on speech and articulation rates. However, we were unable to categorize the difference between speech planning and speech execution in this review as it is often difficult to infer which aspect/s of speech planning are being targeted in research. Although pausing behaviour (Krivokapić et al., 2022) and fluency (i.e. stuttering-like characteristics; Jackson et al., 2021) are cited as being parameters of speech planning, the origin of pauses has previously been attributed both to language difficulties (Bóna, 2014; Burke et al., 2000) and respiratory physiology (Huber et al., 2012). This means that there are several possible definitions of pausing and, in turn, fluency, which could depend on success at all levels of speech production from conceptualization to articulation (Martin & Slevc, 2014). As speech planning lies at the intersection between language and motor speech processes, isolating speech motor planning relative to phonological planning, and indeed language processing, requires careful consideration. For example, in their syllable repetition task, Tremblay et al. (2019b) manipulated the sequential and phonological complexity of syllable sequences. Articulation rate and stability were reduced under more complex conditions, suggesting that both phonological and motor planning are affected by healthy aging. In terms of the role of cognition in speech planning, further research is required, for example by carefully controlling for language and phonological processes.

In MCI patients, the quantity of available evidence was more limited and with significant gaps, particularly regarding speed of processing and working memory. Nevertheless, better global cognitive functioning was associated with faster articulation rate (Lowit et al., 2006). Poorer attentional abilities were also associated with slower speech rate and more dysfluencies (de Looze et al., 2018; Kim et al., 2019), while poorer long-term memory performance predicted more frequent pauses (Kim et al., 2019).

The evidence in MCI may point to language planning deficits rather than problems with motor speech execution. Returning to Node Structure Theory (NST; MacKay, 1982), this could be explained by an age-related breakdown in the connection between higher-level nodes in the mental system and the muscle-movement system. If the muscle-movement system takes longer to be activated, this could result in slower speech and/or more pauses. However, this is suggested tentatively, given the limited motor speech variables and significant gaps in the literature measuring core cognitive domains. It is important for researchers to be aware that reduced speech and articulation rates in speakers can be attributed to both speech and/or language processes, and sensitivity must be exercised when selecting cognitive and speech tasks, as well as speech measures, to ensure compatibility between these three elements, depending on the aims of the research.

In general, there was little opportunity to compare healthy and MCI groups, despite suggestions that cognitive impairment disproportionately affects motor speech performance in MCI (Themistocleous et al., 2020). Measures of speech rate, syllable duration and silent and filled pauses have successfully distinguished between cognitively healthy, MCI, and patients with advanced cognitive decline, based on performance on dementia screening tools (Ambrosini et al., 2019; König et al., 2015; Martínez-Nicolás et al., 2021; Sluis et al., 2020). Future researchers are therefore recommended to evaluate how speech features used in classification studies (e.g. articulation rate, pause measures; Martínez-Nicolás et al., 2021) are related to specific cognitive abilities, rather than only to general cognitive ability, particularly as measured using screening tools.

One common factor could possibly account for declines to fluid cognitive abilities and motor speech production. The prefrontal cortex (PFC) is crucial for top-down integration of behaviour, including across sensory modalities (Knight et al., 1999), and shows age-related changes in activity during a range of cognitive tasks (Cabeza, 2002). Guenther and Hickock (2015) state that, relative to syllable production, the production of longer utterances requires additional brain areas, particularly the left PFC. This suggests that connected speech in older adults could be particularly vulnerable due to degradation in the PFC (Cabeza, 2002). Indeed, Tremblay et al. (2017) reported that complex speech in older adults resulted in activation beyond the sensorimotor areas associated with typical young adults' speech including the Posterior Cingulate Cortex (PCC), an area associated with cognitive control (see also Tremblay & Deschamps, 2016). These findings and our behavioural results align in suggesting that older adults use compensatory behaviour, and show compensation-like activation, to maintain performance in complex speech tasks. Our review also suggests that fluid cognitive abilities (e.g. speed of information processing, attention/executive functioning, working memory) may explain more of the variance in motor speech production compared with crystallized abilities (e.g. vocabulary, semantic knowledge). Still, given the limited quantity of studies investigating these links with motor speech performance, further replication is required to be able to make stronger conclusions.

Empirical evidence in support of a common cause shows increasing interdependence between cognition and sensory modalities in aging (e.g. Li & Lindenberger, 2002). However, this is typically limited to measures of unisensory abilities such as vision or hearing (Monge & Madden, 2016; Wayne & Johnsrude, 2015). The DIVA model of speech motor control (Guenther, 1994; Guenther & Vladusich, 2012) emphasizes the role of auditory and somatosensory feedback for the control and coordination of speech movements at the syllable level, suggesting that speech production requires multisensory integration (also see McGurk & MacDonald, 1976). Hirst et al. (2022) found that multisensory integration during an audio-visual paradigm in older adults was associated with several cognitive functions (memory, processing speed, sustained attention, and executive function), again suggesting more global declines. The production of speech is therefore likely more complex than the lower-level perceptual abilities previously considered within the common cause framework. Tremblay et al. (2019a) describe the neuromotor organization of speech as requiring an interaction between sensorimotor, language, and cognitive/executive processes, including verbal memory and audio-visual attention. How these interactions occur at the behavioural level now requires further attention. In future research, language processing must be controlled in investigations of cognition and motor speech production. It may also be beneficial to control for motor speech functioning when examining cognition and language production.

As many studies included a dual-task paradigm, it is recommended to move away from the narrow view that dual-task studies are a measure of divided attention. As demonstrated here, it is likely that other cognitive and motor functions are involved, and the outcome depends on the complexity of the concurrent task and the speech task together (Belletier et al., 2023). This is in line with Whitfield et al. (2021), who speculated that changes to speech motor control in younger adults may depend on the combined difficulty of two concurrent tasks. Central to multi-component models of working memory (e.g. Baddeley et al., 2020; Logie, 2023) is an attentional ('central executive') component, which is linked with articulation and verbal rehearsal, highlighting how both could be involved in motor speech production. Indeed, executive functions are at the same time unified and diverse, and inhibition is the one factor that loads almost perfectly onto executive function at the latent level (Friedman & Miyake, 2017). This could potentially explain the presently observed relationship between articulation and attention/executive abilities, especially when measured via inhibition. Shen and Janse (2020) investigated the relationship between executive abilities and articulatory control in young adults finding that those with poorer cognitive switching ability were less able to alternate between speech movements. This, and the current research, challenge the notion that motor speech is entirely automatic, as was previously thought (Lo et al., 2020). In addition, both working memory and speech motor control show activation in the dorsolateral PFC (DLPFC), providing neurological evidence of top-down control of speech (Hu et al., 2023; Guo et al., 2017; Nyberg et al., 2022). While age-related changes in working memory negatively affect comprehension during conversational speech (Naveh-Benjamin & Cowan, 2023), our review suggests that age-related cognitive changes may also impact speech production. We note, however, that no included studies administered maximum performance tasks (MPTs) such as rapid repetition of syllables (diadochokinetic; DDK) or sustained vowel tasks. Although not free from criticism, these are amongst the most common methods of measuring articulatory agility and control and maximum phonation time in clinical populations (Kent, 2004). Future research would benefit from extending the work of Shen and Janse (2020) by investigating associations between executive abilities and DDK rates in healthy older adults. Furthermore, it may be of interest to examine the extent to which cognitive abilities are associated with either the laryngeal and/or the articulatory subsystem using MPTs.

4.1. Limitations and future directions

Following recommended guidelines (The CRD, 2009; PRISMA, Page et al., 2021) this systematic review provides a comprehensive narrative synthesis of the available literature investigating the relationship between cognitive and motor speech abilities in older age. The research included can broadly be categorized into those that investigate the effect of increasing cognitive demands on motor speech production, and those that investigate how cognitive decline impacts motor speech production, by comparing healthy older adults to those with MCI. However, by necessity, the review is limited to reports in the English language. Furthermore, there were relatively few high-powered studies and most lacked inclusion of healthy older adults aged over 80 years, limiting the ability to observe the trajectory of speech changes across older age. Given that a large proportion of the data were taken from healthy older adults recruited as age-matched controls in clinical studies (15 of 22 studies), the results reported here may not be fully representative of the healthy older adult population. This is especially true because several included studies reported data from adults younger than 60 in their samples. This was coupled with lack of cognitive screening and small samples. There were also often gaps in the reported demographic information (e.g. education levels; see Table 1) and recruitment strategies (e.g. it was unclear if participants were friends and family of patients). The speech outcomes were likely selected based on the clinical samples and may not adequately represent speech changes in healthy aging. This also explains the heterogeneity across studies, as the clinical samples differed, resulting in a diverse selection of cognitive and speech tasks and speech measures. The field of acoustic measurement of speech is vast (Pommée et al., 2021), which can, to some extent, explain the range of outcomes across studies. When reviewing speech production changes across the lifespan, Tucker et al. (2021) reported that the most prominent findings could be grouped into speech rate, voice, formants, pauses/disfluencies, duration, and amplitude. The variability and inconsistency in previous evidence could be due in part to differences in study design (e.g. cross-sectional vs longitudinal) and definitions of age ranges (Tucker et al., 2021). The current systematic review builds on that of Tucker et al. by identifying the potential cognitive predictors of some speech changes in populations with an average age of 60 or above. Both reviews have stressed the need for clearer definitions of speech measures and methodology to allow for replication and future data pooling for meta-analyses.

Future research should also focus on achieving sufficient statistical power with target sample sizes based on power analyses. Relatedly, as with all research, greater adoption of 'open science' practices (e.g. see Open Science Framework; https://osf.io/), such as pre-registering research, data sharing, and pre-print publications would help protect against selective reporting of results and reduce publication bias. Regarding research design and methods there is a need to implement cognitive screening tests during recruitment with a more thorough consideration of factors that could affect the potential relationship between cognition and speech (e.g. employment, health status, activity engagement, living situation). Incorporating a comprehensive cognitive test battery including both fluid and crystallized cognitive abilities is also recommended as part of functional assessment. Finally, we suggest that a multidisciplinary approach between cognitive and speech scientists could usefully be taken more frequently, to ensure motor speech production and cognition are being assessed appropriately, and to benefit theory development. Niebuhr and Michaud (2015) described the process of collecting speech data as an underestimated challenge. These authors outline that it is crucial to consider individual speaker differences (e.g. physiological, social and linguistic factors), the difficulty of the speech elicitation task and recording conditions. Acoustic analysis also requires specialist expertise that may not be accessible to all disciplines interested in using signal processing techniques to objectively measure speech. Furthermore, some evidence shows that directing attention towards speaking disrupts the automaticity of the articulatory process (Lo et al., 2020), particularly in high-stress environments such as in a lab-based, experimental setting. Attention should be paid to the participant's experience in their environment during testing, to minimize potential confounding from extraneous variables.

Importantly, investigating relationships between cognitive and motor speech ability is challenging due to confounding in the speech task (e.g. Bóna, 2014). At the same time, controlled laboratory-based studies have been criticized due to lack of ecological validity. Well-controlled speech tasks such as sentence repetition may lack 'communicative intent' and fail to capture the essence of speaking (Hazan, 2017). A delicate balance is therefore required to develop controlled investigations that also have practical implications for daily communicative experiences, for example, by investigating how functional changes affect communicative or social participation. Stereotyped expectations of older adults can also occur, based on cues (Ryan, 2010) such as speech style. Understanding that situation-specific cognitive demands may influence older adults' speech could encourage communication partners to interact with older adults in sensitive, non-prejudiced ways. Health care providers may consider limiting administration of secondary tasks to patients while speaking, such as completing forms or assessments. Practical applications such as this could usefully be investigated in future research. Importantly, effective communication is crucial for older adults to adjust to health and lifestyle changes (Yorkston et al., 2010) which might come with retirement, for example. Age-related cognitive decline can negatively impact on communication ability and, in turn, social interaction (Naveh-Benjamin & Cowan, 2023). Indeed, social engagement is associated with better cognitive functioning (Gow et al., 2013; Pichora-Fuller et al., 2015; Oh et al., 2021) and may reduce the risk of dementia (Fratiglioni et al., 2004). Continued theoretical development in this area is therefore required.

4.2. Conclusions

The findings from this systematic review suggest that age-related motor speech differences may be related to global and/or specific cognitive abilities. However, due to the limited and heterogeneous evidence currently available, this may depend on the specific cognitive measure and speech task used. The most robust relationship was observed between attention/executive functioning and articulation, based on measures of articulation rate, accuracy, and speech kinematics. A common cause could potentially be responsible for changes to both cognitive and motor speech production. In future, to develop more comprehensive understanding of the relationship between cognitive aging and motor speech production, researchers should consider a range of appropriate speech tasks and tap into more specific cognitive abilities, particularly as both are fundamental to communication and social interaction.

CRediT authorship contribution statement

Laura Manderson: Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Anna Krzeczkowska:** Writing – review & editing, Methodology. **Anja Kuschmann:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization, Methodology. **Anja Lowit:** Writing – review & editing, Supervision, Conceptualization, Methodology. **Louise A. Brown Nicholls:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization.

Data availability statement

Data supporting the results reported here may be found in supplementary materials.

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Declaration of Interest Statement

The authors report that there are no conflicts of interest or competing interests to declare.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jcomdis.2025.106510.

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