Towards the Speech Features of Mild Cognitive Impairment: Universal Evidence from Structured and Unstructured Connected Speech of Chinese

Tianqi Wang[1], *Chongyuan Lian*[1], *Jingshen Pan*[1], *Quanlei Yan*[1], *Feiqi Zhu*[2], *Manwa L. Ng*[3], *Lan Wang*[1], *Nan Yan*[1]

[1]CAS Key Laboratory of Human-Machine Intelligence-Synergy Systems, Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, China
[2]Department of Neurology, Shenzhen Luohu People's Hospital, Shenzhen, China
[3]Speech Science Laboratory, University of Hong Kong, Hong Kong, China
zfqzsu2004@aliyun.com, nan.yan@siat.ac.cn, lan.wang@siat.ac.cn

Abstract

Language impairment is a sensitive biomarker for the detection of cognitive decline associated with mild cognitive impairment (MCI). Recently, knowledge about distinctive linguistic features identifying language deficits in MCI has progressively been enriched and accumulated. However, the employment of a single speech task to elicit connected speech (e.g., structured vs. spontaneous conversations) might limit the generalization of salient linguistic features associated with MCI. Not to mention the scarcity of reports on analysis of extended speech of Chinese. The present study aimed to examine if connected speech production in both situational picture description and spontaneous self-introduction tasks could be used to distinguish individuals with psychometric evidence of MCI and those who were cognitively intact. Speech samples produced by 75 elderly native speakers of Mandarin Chinese, including 19 with MCI and 56 healthy controls were obtained. Macrostructural aspects of language, including lexico-semantic, syntactic, speech fluency, and acoustics were analyzed by applying the linear mixed-effect regression model. Our study revealed decreasing linear trends in semantic contents and syntactic complexity, as well as significantly greater signs of disfluency and reduced speech production in participants with MCI. The findings extended what was reported in the literature, and carry important implications to the screening and diagnosis of suspected MCI.

Index Terms: mild cognitive impairment, connected speech production, speech features

1. Introduction

With the aging population, Alzheimer's disease (AD) is becoming a central health issue worldwide. It is estimated that the total number of individuals with dementia will reach 82 million in 2030, and dementia is the most common symptom of AD, accounting for 60 - 70% of AD cases [1]. In the absence of effective treatment for AD, identification of the prodromal symptoms of dementia such as mild cognitive impairment (MCI) is of vital importance, as this preclinical period could provide a valuable time window for drug development, risk assessment, and prevention [2-4].

The literature has well-documented that neuropathological changes develop years or decades before AD is diagnosed [5, 6]. While conventional test batteries highlighting functions in verbal fluency and naming (e.g., Boston Naming Test) are useful in identifying moderate to severe AD [7], such tests have not been effective in detecting very early stage of cognitive decline that can be differentiated from typical changes associated with aging [8, 9]. More recent studies examined early disruption of normative patterns and processing of speech and language in patients with MCI in the context of connected speech production [10]. The connected speech is usually elicited in structured conversations constrained in clinical settings (e.g., situational picture description and story narration tasks) or spontaneous conversations in more natural settings (e.g., interviews). The analysis of language performance in connected speech proved to be very useful tools, providing informative data about all linguistic dimensions: phonetic-phonological, lexico-semantic, morpho-syntactic and discourse-pragmatic. Moreover, the analysis of connected language can be considered as an integral part of the cognitive evaluation of individuals who meet criteria of MCI.

Previous studies have revealed that language deficits associated with MCI are very similar to those described in the early stages of AD, mainly manifested in lexico-semantic and pragmatic level of processing [10-14]. Lexico-semantic level disorders are primarily caused by declines in semantic memory, which are dependent upon anterior medial temporal structures and tend to be affected earlier in MCI [15]. Semantic memory difficulties lead to reduced productivity and limited lexical variety in connected speech [16-18], and therefore lexical richness and idea density have been regarded as salient linguistic features identifying language deficits associated to MCI. Deterioration of pragmatics is characterized by less informative discourse, more implausible/irrelevant details and incomplete content elements in situational picture descriptions [13]. Altered features at the pragmatic level could also be identified by using word-based approaches in unstructured conversations [19]. Syntactic levels are also impaired in patients with MCI according to a number of studies [14, 20, 21]. Typical features include reduced sentence length and short utterances, revealing a decrease in the syntactic complexity. Recently, researchers found that acoustic features, which have been rarely investigated, seem to be sensitive biomarkers for early cognitive decline. MCI is known to influence the verbal fluency of the connected speech [22], which manifest itself in longer hesitation and a reduced speech rate [23, 24]. Therefore, several studies performed MCI detection by extracting features such as articulation/speech rate and filled pauses (e.g., [25, 26]).

While considerable efforts have been made to identify disease-specific speech and language abnormalities associated with MCI, most studies employed single speech task to elicit connected speech (structured vs. unstructured). The lack of universal evidence from heterogenous speech tasks might limit the generalization of salient linguistic features that characterize MCI. Besides, reports on analysis of extended speech of Chinese remain scarce. To date, even the most widely used DementiaBank corpus [27] includes very limited speech samples from Chinese patients with "possible" or "probable" AD. Much fewer are speech samples from individuals who are at the prodromal stage of AD.

The present study attempted to investigate if connected speech production in both situational picture description and spontaneous self-introduction tasks could be used to reveal alterations of speech and language patterns in early cognitive decline. Multidimensional features, evaluating lexical, semantic, syntactic and acoustic aspects of speech production, were extracted from structured and unstructured connected speech of Chinese. Specifically, the linear mixed-effect regression model was applied, which allows a systematic approach to incorporate both fixed effects and random effects to deal with categorical grouping factor (MCI vs. healthy control), by-subject variation (e.g., age), by-item variation (picture description vs. self-introduction), and the built-in relationships among the multiple predictor variables. Properly applying this model would have significant advantage of representing connected speech record outside the constrain of specific task setting. Further advantage of such approach is that it would render what was reported in the literature potentially applicable to larger section of speech samples, which carries important implications to the screening and diagnosis of suspected MCI.

2. Methods

2.1. Participants

A total of 75 individuals including 19 elderly (11 F & 8 M) who were diagnosed with MCI, and 56 healthy elderly (29 F & 27 M) controls participated in this study. The MCI participants recruited from the Shenzhen Luohu People's Hospital received comprehensive neuropsychological evaluations and were assigned to the MCI group based on a history of cognitive decline and the results of the mental status examination (i.e., Montreal Cognitive Assessment, MoCA; and Mini-Mental State Examination, MMSE). Participants having no history of psychiatric issues or neurological disorders were also recruited and served as controls. The inclusion criteria were: all participants were above 60 years of age, they had received at least primary school education, and they had no history of taking neuroleptic medication. The study was approved by the Institutional Review Board of Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences. Informed consent was obtained from each participant or their relatives before the experiment.

Table 1 depicts the demographic characteristics of participants, including age, gender, and education level. Note, however, that the two groups were not matched for education level, which can be viewed as one limitation of the study. To confirm that words/vocabularies produced by participants were not sensitive to the level of education, a correlation analysis was conducted, which revealed insignificant correlation between word frequency and education (ρ = .116, p = .156), and weak correlation between vocabulary frequency and education (ρ = -.219, p = .007).

The cognitive tests, including MoCA and MMSE, are commonly used in clinical practice to assess cognitive decline in orientation, encoding (immediate memory), short-term memory, visuospatial and executive abilities, as well as language functioning [28, 29]. Raw scores of the two tests were corrected for age and education, and are reported in Table 1.

Table 1: *Demographic information (mean and SD)*

	MCI **N = 19**	**Normal** **N = 56**	**Statistics**
Age (years)	65.6 (5.7)	67.9 (5.9)	t = -1.47
Gender (F/M)	11/8	29/27	$\chi^2 = 0.213$
Education (years)	10.4 (2.7)	13.3 (2.5)	t = -4.17***
MoCA (30)	23.7 (2.4)	27.8 (1.3)	t = -7.22***
MMSE (30)	25.2 (2.7)	29.2 (1.0)	t = -6.15***

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

2.2. Recording protocol

All participants were required to produce their connected speech during the execution of two tasks. Structured connected speech was elicited using the "Cookie Theft" picture description task from the Boston Diagnostic Aphasia Examination (BDAE) [30], in which participants are asked to describe everything they see in the picture. Unstructured connected speech was elicited by predefined open-ended questions, which direct participants into specific topics concerning family, career, hobbies, etc. To allow for comparison, both tasks were constrained to one minute.

During speech production, the examiner encouraged the participant to keep going if they produced a very limited speech output. All the instructions and interventions were included in the one-minute recording session.

The vocal tasks were recorded in a noise-attenuated room using an external sound mixer (E-MU 0404 USB Audio/MIDI Interface, Creative) connected to a professional microphone (MK4, Sennheiser) which was placed 10 cm from the lips. The samples were digitized with 44100 Hz sampling rate and 16-bit/sample resolution.

2.3. Speech analysis

Speech samples were manually transcribed at the word level by three researchers (TW, JP, and QY) using TextGrid in *Praat*. In order to ensure consistency among transcribers, the TalkBank Codes for Human Analysis of Transcripts (CHAT) [31] protocol was imposed. All analyses were restricted to utterances related to the stimulus picture or open-ended questions. Unrelated utterances such as questions about the task or conversations with the examiner were ignored. Paralinguistic phenomena such as filled pauses (e.g., "uh", "mm", "er", "ah", "zhege", "nage" ["this" and "that" in Chinese]), disfluencies (e.g., false start, hesitation, stuttering), and non-verbal phenomena (e.g., coughing, throat clearing, laughs, inspirations) were also annotated, together with temporal information.

The transcribed materials were then segmented and tagged to a particular part of speech (POS) by Natural Language Processing and Information Retrieval Sharing Platform (NLPIR) [32]. Annotations of syntactic dependencies were achieved by Language Technology Platform (LTP) [33]. Upon completion, automatic annotations were checked by two researchers (TW and JP) to remove errors.

Semantic content of the speech samples in the picture description task was quantified using the human-supplied information content unit (ICU) described in [34]. Thirty-five units, grouped under five headings, were assumed to constitute a complete description of the picture scene, which included three subjects, two places, 16 objects, nine actions, and five relations. Following [19], semantic content of unstructured connected speech was analyzed using Linguistic Inquiry and Word Count 2007 (LIWC; Chinese version) [35], with which words were categorized into five broader domains: linguistic dimensions, psychological processes, relativity, personal concerns, and spoken categories. Each of these word categories includes words representing a particular conceptual domain, and thus ICUs of unstructured speech samples could be quantified.

ICUs in each speech sample was counted by two raters (TW and JP), and good inter-rater agreement was obtained. Consensus on all points of discrepancy was reached later in the study.

2.4. Features

A multidimensional parameter computation was performed on the connected speech samples, extracting lexical, semantic, syntactic, speech fluency, and acoustic features. The parameters used for analysis are summarized in Table 2. Respective definition and explanations of investigated features were reported in previous studies.

Table 2: *Categories of connected speech features*

Lexical	**Semantic**
Total words/characters [16]	Semantic units [19, 34]
POS rate [14]	Idea density [37]
Content density [14]	Idea efficiency [37]
Type-token ratio [14, 38, 39]	
Brunét's index [14, 38]	**Syntactic**
Honoré's index [14, 38]	Utterance length [16, 21]
Word/Vocabulary frequency [39]	Dependent elements linked to the noun [37]
Acoustic	Syntactic complexity [20]
Silence duration [40]	
Speech duration [40]	**Speech fluency**
Voice-silence ratio [14]	Filled pause count/rate [16]
Verbal rate [24]	Disfluency count/rate [23, 37]
Std. phonation rate [24]	

Table 3: *Comparison of connected speech features between individuals with MCI and healthy control (mean and SD in parenthesis) and corresponding regression coefficients (β) and standard error (SE) for the fixed effect of group*

	Picture Description		**Self-Introduction**		**Group**		**Likelihood Ratio Test**	
	MCI	**Normal**	**MCI**	**Normal**	**β**	**SE**	χ^2	***p*-value**
(A) Lexical								
Total words	93.89 (24.3)	118.07 (30.5)	96.42 (26.4)	106.93 (25.6)	-17.630	6.066	8.003	0.005**
Total characters	129.79 (34.7)	167.05 (42.0)	146.37 (38.6)	163.36 (38.7)	-27.932	8.755	9.545	0.002**
POS rate								
Open-class words	0.55 (0.05)	0.57 (0.05)	0.60 (0.09)	0.59 (0.06)	-0.014	0.012	1.229	0.268
Closed-class words	0.45 (0.05)	0.42 (0.05)	0.40 (0.09)	0.41 (0.06)	0.014	0.012	1.229	0.268
Content density	1.39 (0.27)	1.55 (0.35)	1.70 (0.65)	1.56 (0.50)	-0.052	0.092	0.319	0.572
Lexical richness								
Type-token ratio	0.63 (0.1)	0.63 (0.1)	0.67 (0.1)	0.67 (0.1)	-0.007	0.017	0.154	0.695
Brunét's index	47.95 (11.1)	57.92 (13.4)	48.57 (12.2)	52.79 (11.3)	-7.168	2.705	6.713	0.010**
Honoré's index	567.84 (28.7)	589.44 (26.1)	588.51 (21.6)	604.13 (23.4)	-21.325	4.735	17.930	0.000***
Word frequency	0.45 (0.14)	0.50 (0.16)	0.45 (0.13)	0.48 (0.18)	-0.043	0.035	1.492	0.222
Vocabulary frequency	0.29 (0.07)	0.26 (0.04)	0.27 (0.03)	0.23 (0.04)	0.036	0.008	16.424	0.000***
(B) Semantic								
Semantic units	11.00 (4.16)	15.57 (3.95)	11.95 (2.84)	13.63 (2.60)	-3.455	0.651	23.906	0.000***
Idea density	0.12 (0.05)	0.14 (0.04)	0.13 (0.05)	0.13 (0.02)	-0.009	0.008	1.354	0.245
Idea efficiency	0.18 (0.07)	0.26 (0.07)	0.20 (0.05)	0.22 (0.04)	-0.055	0.011	20.818	0.000***
(C) Syntactic								
Utterance length	7.99 (2.03)	8.65 (2.03)	6.27 (1.18)	7.51 (1.52)	-1.072	0.356	8.567	0.003**
Dependent element linked to the noun	1.50 (0.54)	1.62 (0.61)	1.26 (0.60)	1.59 (0.54)	-0.244	0.113	4.484	0.034*
Syntactic complexity	0.74 (0.09)	0.71 (0.10)	0.75 (0.09)	0.75 (0.08)	0.017	0.017	1.000	0.317
(D) Speech fluency								
Filled pause count	2.21 (1.65)	2.85 (3.00)	5.16 (3.82)	4.89 (2.93)	-0.308	0.613	0.252	0.616
Filled pause rate	0.03 (0.02)	0.02 (0.02)	0.05 (0.03)	0.05 (0.03)	0.002	0.006	0.118	0.731
Disfluency	3.37 (2.67)	2.05 (1.61)	1.68 (1.92)	1.34 (1.42)	0.917	0.350	6.581	0.010*
Disfluency rate	0.03 (0.02)	0.02 (0.01)	0.02 (0.02)	0.01 (0.01)	0.011	0.003	12.418	0.000***
(E) Acoustic								
Silence duration	13.55 (5.53)	7.71 (5.03)	12.26 (8.92)	8.24 (4.69)	4.811	1.240	13.724	0.000***
Speech duration	46.64 (5.79)	53.63 (7.82)	48.50 (9.00)	52.68 (5.27)	-5.600	1.494	12.866	0.000***
Voice-silence ratio	4.43 (2.78)	10.11 (6.05)	8.32 (8.47)	9.01 (5.60)	-2.956	1.198	5.857	0.016*
Verbal rate	1.56 (0.40)	1.91 (0.43)	1.59 (0.44)	1.75 (0.40)	-0.259	0.093	7.373	0.007**
Std. phonation rate	2.00 (0.40)	2.18 (0.43)	1.98 (0.37)	2.02 (0.42)	-0.118	0.091	1.677	0.195

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

2.5. Statistical analysis

Linear mixed-effect regression models were applied for each feature separately, allowing for an interpretation of how each fixed effect (i.e., group and age) is related to the outcome measure of interest. Each model was constructed with fixed effects of group (MCI vs. healthy control) and age; and participant and task (picture description vs. self-introduction) as random intercepts. The slope estimates, interpreted as the average effect of cognitive decline, are presented as the beta with standard error (±SE). Likelihood Ratio Test was conducted to compare a full model (with the fixed effect of group) against a reduced model (without the fixed effect of group) to attain *p*-values. Statistical significance was defined as alpha 0.05 for all analysis. The models were developed using *R* and the *lme4* package [36].

3. Results

The fixed effect of group is reported in Table 3. The slopes of the fixed effect of group represent alterations of speech and language patterns due to cognitive decline, where a positive value indicates an increase in such measure and a negative value indicates the opposite effect.

Notably, acoustic parameters, describing quantitative speech and pauses in the signal (e.g., silence duration, speech duration, voice-silence ratio, verbal rate), were significantly modified due to the cognitive decline. Semantic parameters were also substantially altered in participants with MCI. For instance, the number of semantic units was reduced, resulting in low idea efficiency. Recall that syntactic parameters were designed to investigate the structural complexity of utterances. The present data revealed that despite insignificant alterations in the overall syntactic complexity in MCI utterance, reduced utterance length and less complex relations among noun phrases, appeared to be a result of early cognitive decline. Results from linear mixed-effect regression models also indicate significant signs of disfluency in individuals with MCI. For that, the number and proportion of repetition, false start, and repairs could also distinguish MCI from normal individuals.

On the contrary, lexical features that examine lexical knowledge and retrieval, were poorly modified during the cognitive decline, with the notable exception of vocabulary frequency. While the detection of MCI based on POS has been well-established in the literature of Indo-European languages (e.g., [14, 38, 39]), the present study did not provide evidence for a reduced proportion of open-class words (i.e., nouns, verbs, adjectives, and adverbs) and an increased proportion of closed-class (grammatical function) words in the connected speech produced by Chinese speakers with MCI. Besides, features concerning lexical richness were rather contradictory, as lower Honoré's index suggests lower lexical diversity in the MCI group, while a decreasing Brunét's index indicates richer vocabulary in the MCI group. The widely accepted type-token ratio revealed no significant difference in terms of the lexical richness between the two groups. As such, lexical features of the connected speech of Chinese may not serve as sensitive and reliable predictors of cognitive decline associated with MCI.

4. Discussion and Conclusion

Early detection of cognitive decline is a widely shared goal among researchers as a response to the aging society, and the focus is rapidly moving from the conventional neuropsychological language tests, such as lexical and semantic access tasks, to the analysis of connected speech produced in more natural settings. While increasing interest is directed towards the exploration of speech and language alterations associated with MCI in the past decades, two issues still need to be resolved before these novel approaches can be applied to the clinical practice. The first one is the universal applicability of linguistic features among different tasks (e.g., structured vs. unstructured conversations), and the other is the generalization of the salient linguistic features associated with MCI to the connected speech of different languages.

A contribution of the present study derived from the use of both situational picture description and spontaneous self-introduction tasks to elicit structured and unstructured connected speech. The linear mixed-effect regression models were separately constructed for each feature, which took into consideration of the random factor due to task-specific idiosyncrasies. Thus, linguistic features showing significant alterations in individuals with MCI were no longer constrained to a certain speech task. With wider applicability, salient linguistic features become more meaningful biomarkers for early cognitive decline.

In addition, the present study provided evidence to the emerging but still controversial literature, supporting that acoustic, semantic, and syntactic features, as well as speech fluency parameters could discriminate MCI from control participants, and at the same time invalidating lexical features as sensitive markers of language alterations in the connected speech of Chinese. It should be noted, however, that the lack of significance in the well-established lexical features such as content density, type-token ratio might also derive from the intact cognitive functions of lexical retrieval among our selected participants with MCI. Thus, even salient features need to be interpreted with caution, as significant modifications in such features may come from various sources. Neurophysiological studies together with speech production tasks are necessary to confirm whether the selected feature could indicate the nature of the deficit.

To sum up, the present study revealed that reduced ability in speech production, with signs of increased disfluency, and decreasing linear trends in semantic contents and syntactic complexity were prominent features associated with MCI. Universal evidence was obtained from structured and unstructured connected speech of Chinese, which extended what has been reported in the literature and carries important implications to the screening and diagnosis of suspected MCI.

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