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Effects of age and dementia on temporal cycles in spontaneous speech fluency

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Abstract

Spontaneous speech of healthy adults consists of alternating periods of fluent and hesitant segments, forming *temporal cycles* in speech fluency. The regularity of these cycles may be related to the functioning of brain networks during speech planning and execution. This paper investigates the theoretical link between human cognitive functioning and temporal cycles in speech production using a quantitative time series analysis to characterize the regularity and frequency of temporal cycles in adults with differing levels and etiology of cognitive decline. We compare spontaneous speech of adults without a neurological diagnosis, both older and younger, to that of adults with frontotemporal lobar degeneration (FTLD). Two measures of temporal cycle frequency (mean and mode) calculated from the power spectrum of speech fluency represented as a time series were found to be associated with subjects' age, regardless of diagnosis of dementia. Two measures of periodicity (g-statistic and rhythmicity-index), as well as mean frequency, differentiated between adults with and without dementia. Our study confirms the presence of regular temporal cycles in spontaneous speech and suggests that temporal cycle characteristics are affected in different ways by declines in cognitive functioning due to dementia and aging.

Section 1: Introduction

Hesitations constitute a characteristic feature of spontaneous speech, as compared to read speech. In a typical conversation, hesitations occurring with normal frequency and duration do not present a problem for the listener in understanding the interlocutor's message. In fact, hesitations are an important part of communication for both the speaker and the listener. This paper describes an investigation of hesitations in spontaneous speech, focusing on the association between the patterns of alternations between hesitant and fluent speech (i.e., *temporal cycles*) and cognitive decline associated with aging and dementia.

Hesitations include unfilled pauses (silences not attributable to articulation constraints), filled pauses (e.g., "um," "ah"), repetitions, false starts, vowel lengthening, throat-clearing, laughter, and certain body gestures (Shriberg, 1994; Clark, 1996). One function of hesitations is to allow the speaker time to plan the content and form of an upcoming utterance (Butterworth, 1980; Fox Tree & Clark, 1997; Levelt, 1989). More hesitations are

found near utterances that are less routine and thus more cognitively demanding (Arnold, Wasow, Ginstrom, & Losongco, 2000; Freud & Strachey, 1938; Goldman-Eisler, 1958a; O'Connell, Kowal, & Hörmann, 1969). Hesitations are also found more often at the beginnings of utterances, and in longer utterances (Oviatt, 1995).

While a speaker is processing her next utterance, she has the choice to remain silent, or to fill the silence with vocalized “filler material.” A speaker may employ a spoken hesitation as a conversational strategy in order to retain the listener’s attention, signaling to the listener that the speaker is not yet ready to give up the floor (Erbaugh, 1987; Maclay & Osgood, 1959; Shriberg, 1994), although the utility of hesitations from the listener’s perspective is still under debate (Arnold, Fagnano, & Tanenhaus, 2003; Bortfeld, Leon, Bloom, Schober, & Brennan, 2001; Watanabe, Hirose, Den, & Minematsu, 2008; Corley & Hartsuiker, 2003). Danemann (1991) found that speakers with greater working memory span tended to use fewer hesitations. Hesitations have also been found to be related to the contextual probability and frequency of the words following the hesitation (Beattie, 1983; Goldman-Eisler, 1958b, 1967, 1968; Lounsbury, 1954), as well as boundaries of various units of syntactic and discourse structure (Boomer, 1965; Cook, 1977; Downing, 1970; Grosjean, 1979; Hawkins, 1971; Heeman & Allen, 1997; Shriberg, 1994).

The functions of vocalized and silent pauses often overlap, as do the explanations for these various forms of hesitations (see, e.g., Beattie, 1980; Downing, 1970; Kircher, Brammer, Levelt, Bartels, & McGuire, 2004; Maclay & Osgood, 1959; Shriberg, 1994). Both vocalized and silent pauses have been previously found to appear at regular intervals in spontaneous discourse, alternating with more fluent speech (Warner, 1979; Roberts & Kirsner, 2000); therefore, in the current study, we do not distinguish between vocalized and silent pauses, and treat them as part of a single cognitive phenomenon—hesitation.

1.1 Temporal Cycles in Speech Fluency

Patterns of alternations between hesitant and fluent speech sometimes referred to as temporal cycles have been extensively investigated since the mid-1960s (see e.g., Butterworth, 1975; Goldman-Eisler, 1968; Henderson, Goldman-Eisler, & Skarbek, 1966). Previous literature suggests that temporal cycles, also called *cognitive rhythms*, reflect alternating demands on cognitive resources during the semantic planning stage of speech production (Greene & Capella, 1986; Levelt, 1989; Roberts & Kirsner, 2000). Specifically, Greene & Capella (1986, p. 143) propose a link between the speaker’s plan consisting of one or more cognitively demanding transitions between communicative sub-goals and the transitions to and from fluent and hesitant speech segments. Similarly, Levelt (1989, p. 126) proposes that the more hesitant portions of temporal cycles reflect *macroplanning* (“information retrieval and inference”) while the more fluent portions reflect *microplanning* (“finalizing messages for expression”). Macroplanning is said to require greater attention and executive control and therefore fewer cognitive resources can be devoted to maintaining fluency while macroplanning is taking place. However, when a topic of conversation is highly familiar to the speaker, macroplanning tends to be less effortful, and therefore temporal cycles may not be observed (Levelt, 1989, p. 128).

If we assume that temporal cycles are the result of competition for cognitive resources, we would expect to see differences in temporal cycles for populations whose cognitive resources are limited due to, for example, neurological disorders or the natural aging process, compared with healthy younger populations. For example, working memory is widely believed to be of critical importance in many aspects of language processing (Stine, Cheung, & Henderson, 1995; Van der Linden, Hupet, Feyereisen, Schelstraete, Bestgen, et al., 1999). There is evidence that working memory is often affected in patients with neurological disorders, and has been found to be one of the main mediating variables in the

progressive loss of language production abilities associated with aging (Van der Linden, et al., 1999).

Although temporal cycles in speech fluency have not been investigated in older adults, there are studies of other measures of dysfluency for this population. Smith, Wasowicz, and Preston (1987) have found that healthy older adults' sentences are spoken on average 20% more slowly than healthy younger adults' sentences. It has also been shown that older adults' spontaneous speech contains more hesitations and is less syntactically complex than that of younger adults (e.g., Balota & Ducheck, 1988; Bortfeld, et al., 2001; Bowels & Poon, 1985; Burke, MacKay, & James, 2000; Kemper, Herman, & Lian, 2003; Norman, Kemper, Kynette, Cheung, & Anagnopoulos, 1991).

We are not aware of any other published studies that compare temporal cycles in speech fluency of neurologically-impaired subjects to those of subjects with no neurological diagnosis. However, a number of studies have investigated other patterns of fluency in cognitively-impaired subjects. Hird and Kirsner (2010) investigated rhythmic patterns in length of silence–non-silence lognormal distributions for three aphasic subjects. They found that non-brain damaged subjects' short pauses (mean = log 4.21 ms, sd = log 0.59) and long pauses (mean = log 6.61 ms, sd = log 0.68) fell into very similar distributions, while the three aphasic subjects' short and long pause distributions deviated from controls' pause distributions in different ways for each aphasic subject. No distinctions were made between hesitation-related pauses and articulatorily-motivated pauses nor between fluent speech and vocalized hesitations. A study examining "prosodic tempo" found that aphasic subjects' use of conversational repairs differed depending on whether their conversational partner was familiar or unfamiliar to them, whereas healthy subjects' repairs did not change based on familiarity with conversational partner (Dressler, Buder, & Cannito, 2009). Another study showed that there was no difference between amnesic subjects and healthy subjects with respect to fluency rates, although healthy subjects did have significantly longer speech times (Robertson & Kirsner, 2000). These studies are important for understanding how cognitive impairments relate to linguistic phenomena, but were not specifically designed to measure temporal cycles of fluent speech and hesitant speech (including vocalized hesitations) in spontaneous speech.

The original procedure for analyzing temporal cycles involved plotting fluent speech time against hesitant speech time and subsequently measuring by hand the duration of estimated cycles. The method of temporal cycle quantification based on this type of plot has been called the "Henderson method," after Henderson et al. (1966). In the Henderson method plot shown in Figure 1, the first cycle begins with about 11 seconds of relatively fluent speech (including the shorter hesitant portions within those 11 seconds), and ends with about 13 seconds of relatively hesitant speech (including the shorter fluent portions within those 13 seconds), for a total first cycle of about 24 seconds. For healthy individuals, average temporal cycles have been generally found to range from 10 to 30 seconds (Beattie, 1980; Butterworth & Goldman-Eisler, 1979; Henderson et al., 1966; Levelt, 1989; Merlo & Barbosa, 2010; Roberts & Kirsner, 2000).

The major complaints leveled against the original method of temporal cycle quantification described above were that it was highly subjective, inconsistent, and difficult to automate (Kowal & O'Connell, 1985; Power, 1983; Schwartz & Jaffe, 1968). Warner (1979), Greene and Capella (1986) and Roberts and Kirsner (2000) have proposed and tested objective approaches based on time-series analysis to the search for temporal cycles. While these statistically-based studies have also found temporal cycles similarly to the studies that had relied on visual examination of graphs representing fluent and dysfluent speech, their results differ with respect to the periodicity and frequency of the cycles. Warner (1979) found

periodic fluent-nonfluent patterns at the lower 3-6 minute frequency but not at the higher 8-25 seconds range identified by Roberts and Kirsner (2000). A possible explanation for this discrepancy (provided by Greene and Capella (1986)) is that Warner's subjects were instructed to speak for a relatively long period of time (40 minutes) on a topic of their choosing. The lack of control over the topic may have resulted in masking any possible temporal cycles at the higher frequencies. Roberts and Kirsner (2000) asked their subjects to talk about themselves for approximately 5 minutes – a shorter and slightly more constrained task. The task used by Greene and Capella (1986) in which the subjects were instructed to speak on a predefined topic (an argument in support of a proposal for a congressional bill) is somewhat similar to the picture description task used in the current study in terms of single topic maintenance. However, the task that was closest to the one reported in this paper was used by Merlo and Barbosa (2010) who also utilized time series analysis to successfully identify periodicity in temporal cycles in Brazilian Portuguese for 5 healthy adult males. The frequency of the cycles reported by Merlo and Barbosa (2010) ranged between 9 and 13 seconds.

1.2 Frontotemporal Lobar Degeneration

Frontotemporal lobar degeneration (FTLD) is a neurodegenerative disorder, similar to Alzheimer's Disease (Lindau, Almkvist, Kushi, Boone, Johansson, et al., 2000), and comprises four variants with different linguistic and social consequences (Knopman, Kramer, Boeve, Caselli, Graff-Redford, et al., 2008). The behavioral variant (bvFTD) affects mainly social function and executive control, while syntax and phonology remain relatively intact. Progressive non-fluent aphasia (PNFA) affects fluency and grammaticality of speech. Progressive logopenic aphasia (PLA) is characterized by fluent aphasia with anomia but intact word meaning and object recognition. Semantic dementia (SD) includes aphasia characterized by loss of word meaning and object recognition. Overlap between language manifestations in the four variants makes the diagnosis of FTLD challenging; however, language remains one of the primary sources of diagnostic information on a patient's initial presentation to the physician's office. Language-related tests of FTLD variants currently include measures of hesitancy; speaking rate; syntactic and morphological complexity; ratio of nouns, verbs, and pronouns; as well as semantic and pragmatic features (Ash, Moore, Vesely, Gunawardena, & McMillan, 2009; Bird, Lambon Ralph, Patterson, & Hodges, 2000; Gorno-Tempini, Murray, Rankin, Weiner, & Miller, 2004a; Grossman, 2002; Hodges, Patterson, Oxbury, & Funnell, 1992; Neary, Snowden, Gustafson, Passant, Stuss, et al., 1998; Pakhomov, Smith, Marino, Birnbaum, Graff-Radford et al., 2009; Pakhomov, Smith, Chacón, Feliciano, Graff-Radford et al., 2010; Peelle, Cooke, Moore, Vesely, & Grossman, 2007).

Given that temporal cycles in speech are said to be affected by cognitive resource demands, we predict that those populations whose cognitive resources may be limited in some way, either by the natural aging process or by a neurological impairment, will show greater irregularity in temporal cycles corresponding to the age and the severity of the impairment, as compared to younger, neurologically unimpaired populations. As this prediction has never been tested, nor any similar predictions, we cannot know whether aging or dementia will have a greater effect on temporal cycles. However, the link between regular temporal cycles and the perception of fluency might lead us to predict that populations subjectively judged to be less fluent than the average speaker (e.g., the FTLD population, especially PNFA and PLA) would show the greatest irregularity in temporal cycles. More specifically, we expect this to be the case because FTLD phenomenology arises as a result of focal damage to either frontal (bvFTD, PNFA) or temporal (PLA, SD) brain networks (Farag, Troiani, Bonner, Powers, Avants, et al., 2010; Gorno-Tempini, Dronkers, Rankin, et al. 2004b; Mesulam, Weineke, Rogalski, Cobia, Thompson, et al., 2009). Generally, frontal

networks are associated with fluency and grammaticality of speech production, whereas temporal networks are more closely related to semantic processing (Price, 2000). Damage to either or both of these networks disrupts fronto-temporal interactions and is likely to manifest itself in decreased speech fluency overall and increased irregularity of alternations in fluency patterns.

Until now, no attempts have been made to quantify temporal cycles in order to compare groups of different ages and different levels of neurological impairment. In a previous study, we examined durational and frequency characteristics of silent pauses and other types of dysfluencies in spontaneous speech of FTLD patients (Pakhomov, Smith, Chacón, Feliciano, Graff-Radford, et al., 2010). We did find significant differences in both durational (mean pause duration) and frequency (pause-to-word ratio) characteristics between the diagnostic groups. However, these characteristics provide only a part of the explanation for the association between speech fluency and neurological impairment. Assuming that previous studies of dysfluency distributions over time via time series analysis are correct in finding periodic alternations in fluency, we would expect that capturing both durational characteristics of dysfluencies and the patterns of their distribution over time may better reflect the cognitive processes underlying speech production. Thus a time series analysis may prove to be a more comprehensive approach that will help us better understand cognitive decline due to aging and dementia. Therefore, we extended Roberts and Kirsner's (2000) methodology in order to characterize various aspects of temporal cycles using a time series analysis, and investigate whether these characteristics are associated with age and/or a diagnosis of dementia. To this end, we developed a semi-automated time series analysis procedure to quantify temporal cycles appearing in spontaneous speech samples, based on two measures of periodicity (r-index and g-statistic) and two measures of frequency (dominant and mean frequencies).

The main objective of this study was to determine if older adults without a neurological diagnosis, younger adults without a neurological diagnosis, and adults with a diagnosis of FTLD display differential temporal cycle characteristics. We expected to find significant differences in temporal cycle characteristics correlating with cognitive decline associated with age and dementia.

Section 2: Experiment

2.1 Participants

A total of 70 adult native speakers of English (35 women, 35 men) participated in this study. Forty-five of those participants (21 women, 24 men; mean age 64.8 years, $sd=8.64$) were clinically diagnosed with one of the four variants of FTLD (bvFTD $n=17$; PNFA $n=12$; PLA $n=5$; SD $n=11$) at the Mayo Clinic in Rochester, Minnesota. The remaining 25 participants (14 women, 11 men; mean age 51.8 years, $sd=22.9$) served as a control group and consisted of volunteers who completed a neuropsychological assessment of spontaneous speech. This control group consisted of 11 elderly nursing home residents (9 women, 2 men) and 14 younger community-dwelling adults (5 women, 9 men). None of the 25 control group volunteers had a diagnosis of dementia at the time of enrollment. Absence of a diagnosis of dementia in the nursing home subjects was determined by the authors from available medical records. The Minimum Data Set¹ (a clinical assessment instrument used in nursing homes on a quarterly basis to monitor health of the residents) was used to ascertain that the nursing home subjects had no receptive or expressive language deficits (scales C4 ["Making self understood"] and C6 ["Ability to understand others"]) were used for this purpose).

¹<http://www.cms.gov/NursingHomeQualityInits/downloads/MDS20MDSAllForms.pdf>

2.2 Clinical Dementia Rating Scale

FTLD patients were assessed using FTLD-modified Clinical Dementia Rating scale that included a language-specific sub-scale (CDRL) (Knopman, Kramer, Boeve, Caselli, Graff-Redford, et al., 2008). The score of 0 on the CDRL indicates normal speech and comprehension; 0.5 indicates minimal but noticeable word finding problems, minimal dysfluency, and normal comprehension; 1 indicates mild word finding problems that do not significantly degrade speech, or mild comprehension difficulties; 2 indicates moderate word finding problems that interfere significantly with communication, moderate dysfluency, and comprehension difficulty; and 3 indicates severe deficits in word finding, expressive speech and comprehension, making conversation virtually non-existent.

2.3 Data Collection

Spontaneous speech samples were collected from the subjects using a standard Boston Diagnostic Aphasia Examination (Goodglass & Kaplan, 1972) picture description task, with the “Cookie Theft” stimulus shown in Figure 2.

Instructions given to subjects were as follows: “Tell me everything you see going on in this picture. Try to speak in sentences.” Recording was stopped after subjects indicated completion or after 30 seconds of silence. Speech was recorded digitally for older and younger control groups and onto cassette tape with subsequent digitization for FTLD patients. The speech was then converted to a 16 bit 16 KHz PCM waveform and subsequently transcribed verbatim and manually aligned with the speech signal by a linguist trained in phonetic analysis. The mean duration of the descriptions was 89.4 seconds (SD = 53.4) with the shortest description of 27.5 seconds and the longest – 271.6 seconds. The alignment was performed using Praat (Boersma & Weenink, 2009). Fluent speech and hesitation phenomena were tagged during the transcription and alignment process using a classification scheme (shown in Table 1) based on a combination of the coding systems from Tingley, Kyte, Johnson, and Beitchman (2003) and Saffran, Berndt, and Schwartz (1989). False starts (e.g., “*I whu-* I went”), coughs, throat-clearing, filled pauses, unfilled pauses, laughs, and repetitions were classified as hesitations. For the purposes of the analysis presented in this paper, it is important to note that research involving silent pauses suggests defining as hesitations only silent pauses greater than 150-200 milliseconds in duration in order to avoid capturing purely articulatorily-conditioned pauses (e.g., silences of ~80 milliseconds due to stop consonant closure/release) (Forrest, Weismer, & Turner, 1989; Levelt, 1989; Stevens, 2000). We used a conservative threshold of 150 milliseconds to define a silent pause. Neologisms, mispronunciations, circumlocutions, and parenthetical remarks were classified as fluent speech. Inter-rater reliability between two coders was calculated using 20 percent of the total speech samples (14 out of 70 narratives), randomly selected, with an agreement rate of 93.1% (Cohen’s kappa = 81.5, $p < .001$).

The transcription and alignment process resulted in a time-stamped representation of each speech sample illustrated in (1) below.

(1)

Start time	End time	Coded word	Duration
6152.8479	6373.9302	S_the	221.0823
6373.9302	6692.4387	S_water	318.5085
6692.4387	6988.4642	F_ah	296.0255
6988.4642	7119.6147	the	131.1505

Start time	End time	Coded word	Duration
7119.6147	7561.7794	water's	442.1647
7561.7794	8554.7764	overflowing	992.9970

The first two columns represent the start and end times (in milliseconds) of each element in the transcript. The third column contains the textual representation of the element. The last column is the element's duration (in milliseconds).

2.4 Signal Processing

Manual alignments were first processed to classify each element as either fluent or a specific type of hesitation (refer to coding scheme in Table 1). In subsequent analyses, we treated elements tagged as T_, F_, S_, SIL, and R_ as hesitant speech and all other elements as fluent speech, resulting in the following representation of the segment previously shown in (1):

(2)

Start time	End time	Final coding	Duration
6152.8479	6373.9302	HESITANT	221.0823
6373.9302	6692.4387	HESITANT	318.5085
6692.4387	6988.4642	HESITANT	296.0255
6988.4642	7119.6147	FLUENT	131.1505
7119.6147	7561.7794	FLUENT	442.1647
7561.7794	8554.7764	FLUENT	992.9970

The time stamped elements, as shown in (2), were divided into samples using 200 ms frames with subsequent smoothing using an order 22 moving average (~ 4.4 seconds at 200 ms frames) following the methodology proposed by Roberts and Kirsner (2000). The resulting signal was represented as a time series with subsequent mean subtraction and trend removal by fitting a linear model to the time series and using the residuals to construct a periodogram (spec.pgram function in R with log parameter set to 'FALSE' and taper parameter set to zero).

2.5 Temporal Cycle Quantification

The power spectrum obtained from the periodogram as described in the previous section can be used to determine if there is evidence of *periodicity* (i.e., regular alternations between fluent and hesitant speech at a certain frequency) as opposed to *cyclicity* (i.e., repeating but not necessarily regular alternations). A periodic process results in a clear dominant peak at a certain frequency in the periodogram. An example of a perfectly periodic signal is provided in Figure 3a along with an example of random white noise in Figure 3b and an actual fluency signal, somewhere between perfectly periodic and perfectly random, from a healthy control subject that participated in this study in Figure 3c. To determine if the alternation between hesitant and fluent speech in our samples was in fact periodic, we examined each periodogram for the presence of a dominant peak by calculating the g-statistic (Warner, 1998). The g-statistic is defined as the ratio of the peak's amplitude to the sum of all amplitudes (total volume) in the power spectrum. Thus, greater g-statistic values indicate greater concentration of power at a single frequency and provide stronger evidence of periodicity. Fisher's test for statistical significance ($\alpha = 0.01$) was then used to

determine if the distribution of the peaks in the power spectrum is significantly different from white noise.

In addition to classifying the signal as periodic/apperiodic using the g-statistic, we experimented with the following characteristics of the periodogram with respect to their sensitivity to age, sex and neurological impairment differences between the participant groups:

- a. Mean – the principal frequency of the periodogram treated as a probability distribution and defined as follows using Hahn and Shapiro's (1967: 42-46) notation:

$$\begin{aligned} vol &= \sum_i a_i && (\text{volume}) \\ \bar{a}_i &= a_i / vol && (\text{scaled amplitude}) \\ mean &= \sum_i \bar{a}_i \cdot f_i && (\text{mean frequency}) \end{aligned}$$

where $a(i)$ denotes the amplitude and $f(i)$ denotes the frequency of the i -th peak in the power spectrum.

- b. Mode - the frequency at which the tallest peak in the spectrum was found.
- c. R-index – an index of rhythmicity defined as the ratio of the volume concentrated in a certain range of frequencies to the total volume. The range of frequencies was set to between 8 and 25 seconds, following Roberts and Kirsner's (2000) finding that most subjects' cycles of hesitant and fluent speech were within this range.

2.6 Statistical Analysis

Due to relatively small sample sizes, we used a more conservative non-parametric Wilcoxon rank-sum test to test for differences between groups. Spearman's rank correlation was used to assess the associations between various behavioral performance measurements. Adjustment for possible confounders when testing for associations between variables was done using logistic regression. All statistical analyses as well as time series analyses were performed using the R statistical software package (version 2.11.0).

Section 3: Results

3.1 General Group Characteristics

The mean age of the 45 FTLN patients (64.8 years, $sd = 8.64$) was significantly different ($p = 0.010$) from the mean age of the control group (51.8 years, $sd = 22.9$). The mean duration of speech on the picture description task was 106 seconds ($sd = 58$ seconds) for the controls and 72 seconds ($sd = 44$ seconds) for the FTLN group. The difference between mean duration for the two groups is significant ($p = 0.013$). No significant differences between these two groups were found with respect to the sex of the participants ($p = 0.36$). Due to significant differences between the groups by age and speech duration, these two variables were included as dependent variables in logistic regression modeling along with the variables of interest (g-statistic, mean, mode and r-index). The results of logistic regression modeling are described in the next section.

3.2 Differences between FTLN and control groups

3.2.1 G-statistic—We first tested each subject's speech sample in both the FTLN and control groups for evidence of periodicity using the Fisher's test of the g-statistic value. For the control group, 19 out of 25 speech samples (76.0%) indicated evidence of periodicity (p

< 0.01). For the FTLT group, 34 out of 45 samples (75.5%), indicated evidence of periodicity ($p < 0.01$). Thus both groups contain roughly the same proportion of periodic speech samples. Informal observations of the aperiodic samples suggested that these samples were produced for reasons that differ between the groups. The subjects that failed the Fisher's test in the control group tended to have shorter picture descriptions with long pauses between sparse utterances. The mean duration of the aperiodic samples in the control group was 65 seconds, which is almost one standard deviation lower than the overall mean for this group – 112 seconds ($SD = 60$). The mean duration of aperiodic samples in the FTLT group (61 seconds), however, was also lower but fairly close the group mean (74 seconds; $SD=47$). Further examination of the diagnoses in this group revealed that the aperiodicity of the samples in this group is most likely to be related to the type of aphasia because more than half of these samples (6 out of 11) came from patients with primary diagnosis of PNFA.

Further analysis for all variables was restricted to those samples that were found to have evidence of periodicity. The differences between the two groups with respect to the value of the g-statistic itself remained significant after filtering the samples for periodicity ($W=201$, $p = 0.023$). Univariate logistic regression analysis was consistent with the Wilcoxon rank-sum test ($p = 0.060$); however, after adjusting for age and duration in a multivariate model, the g-statistic variable did not approach significance ($p = 0.608$).

3.2.2 Mean—The average of the principal radial frequency across the power spectra was 0.030 radians per cycle ($sd = .005$) for the control group and 0.036 radians per cycle ($sd = .007$) for the FTLT group. The difference between these groups was significant ($W = 152$, $p = .001$) and remained significant on univariate ($p = 0.005$) and adjusted for age and duration multivariate logistic regression analyses ($p = 0.009$). Averaged power spectra with averaged mean and mode frequencies are illustrated in Figure 4. The spectrum for the control group contains two pronounced peaks suggesting the presence of subgroups. This is further addressed in the subgroup analyses section below.

3.2.3 Mode—The average mode of the power spectra was 0.012 radians per cycle ($sd = 0.0011$) for the control group and 0.0089 radians per cycle ($sd = 0.0014$) for the FTLT group, as shown in Figure 5. The difference between these groups was not significant ($W = 367.5$, $p = 0.414$) and remained so on univariate ($p=0.590$) and adjusted for age and duration multivariate logistic regression analyses ($p = 0.743$).

3.2.4 R-index—The average r-index was 0.428 ($sd = 0.093$) in the control group and 0.360 ($sd = 0.114$) in the FTLT group, also shown in Figure 5. The difference between these groups was found to be significant ($W=434$, $p = 0.039$). Subsequent univariate logistic regression analysis was consistent with the Wilcoxon test ($p = 0.039$); however, the addition of age and duration to the model resulted in an increased p-value of the r-index variable to 0.087.

The results for all comparisons between the FTLT and control groups are summarized in Table 2.

3.3 Subgroup analyses

3.3.1 FTLT—No significant differences among the four variants of FTLT were found for any of the four power spectrum measurements: g-statistic, mean, mode and r-index. However, there was a strong negative correlation between the g-statistic and the Language Clinical Dementia Rating (CDR-L) assessment scores (Spearman $r = -0.5$, $p=0.002$) indicating an association between the g-statistic and the severity of impairment evident in

FTLD patients' language. These results are summarized in Table 3. We further tested the association between CDR-L and the g-statistic by dichotomizing the CDR-L variable into severe and mild-moderate impairment using a score of 1.5 as a cutoff and subsequently using the new dichotomized variable as the outcome in a logistic regression model with the g-statistic and age as covariates. The modeling results indicate that the g-statistic is a significant predictor of language impairment severity ($p = 0.022$) and age is not ($p = 0.728$ when both variables are included in the model and $p = 0.523$ when age was used in a univariate analysis).

3.3.2: Controls—The analysis of the differences between control group and the FTLT group showed that age was a strong predictor in logistic regression models that included age, duration, and one of the four temporal cycle power spectrum measurements. Participants in our control group were drawn from two different populations and differ significantly in age: one subgroup contained predominantly younger subjects (mean age: 34.7 years, $sd = 11.7$), whereas the other consisted of older subjects (mean age: 75.2 years, $sd = 7.9$). However, the ages of the participants in the combined control group were normally distributed around the mean of 51.8 years ($sd = 22.9$). We tested for associations between the four measurements extracted from the power spectrum and the age of the participants, independent of cognitive impairment due to dementia. We found that age was negatively correlated with the mode (Spearman $r = -0.46$, $p = 0.047$) and the mean (Spearman $r = -0.48$, $p = 0.036$) of the frequency distributions. No significant correlations were found with g-statistic or r-index variables (see Table 4 for a summary of these subgroup results).

The mean age of men in the control group was 41.5 years ($sd = 18.9$), whereas the mean age of women in this group was 59.2 years ($sd = 23.3$). This difference was not statistically significant ($p = 0.085$), but due to the relatively large magnitude of the difference (~20 years), we performed additional testing for associations between the four power spectrum measurements and age of the participants by modeling age using linear regression with sex of the participants as a covariate. The results of linear regression modeling confirmed the correlation results unadjusted for sex. The mode ($p = 0.018$) and the mean ($p = 0.021$) of the frequency distributions were found to be significant predictors of age while controlling for the sex of the participants.

The association between the mode and the mean frequency with age is consistent with the finding of two clearly pronounced peaks in the averaged power spectrum for this group (see Figure 4). Using the median age of 50 years, we generated averaged power spectra for the younger and the older control subgroups as illustrated in Figure 5.

Section 4: Discussion

The contribution of this study is two-fold. First, it confirms the results of previous work on objective temporal cycle quantification using time series analysis, conducted by Roberts and Kirsner (2000) and Merlo and Barbosa (2010). Second, this study is the first to extend the methodology developed by Roberts and Kirsner (2000) to investigate the effects of age and dementia on temporal cycles in spontaneous speech production. We found evidence of differences in temporal cycle periodicity between adults with FTLT and adults with no neurological diagnosis, as well as differences in temporal cycle frequency between older and younger unimpaired adults. While the analysis presented in this paper may be used to quantify in an objective and reproducible fashion speech fluency manifestations of cognitive decline associated with aging and dementia, it does not necessarily demonstrate that FTLT or the primary progressive aphasia associated with FTLT has a unique and specific impact on temporal cycles. In its current state, this measure cannot yet be used as a clinical metric for diagnosis of FTLT. Instead, these are preliminary observations made in a single brain-

injured group that need to be confirmed in other FTLN patient groups as well as tested in other neurologically-impaired populations.

Our results demonstrating the presence of periodic alternations between fluent and hesitant speech on a picture description task are consistent with those obtained by Roberts and Kirsner (2000) and Merlo and Barbosa (2010), who present objective evidence for the existence of temporal cycles in other types of spontaneous speech. We followed the basic procedure outlined in Roberts and Kirsner, using time series analysis to identify periodic repetitions of fluent and hesitant speech, rather than using the previously pervasive (and highly subjective) Henderson method. While Roberts and Kirsner investigated only healthy younger adults, we found that their procedure could successfully be extended to older adult populations and populations with FTLN. In addition, we greatly increased the number of subjects and therefore the statistical power of the findings, relative to Roberts and Kirsner (2010) study. The frequency of alternations between fluent and dysfluent speech in our study is similar to that reported by Roberts and Kirsner (2000) and Merlo and Barbosa (2010) but different from the much longer frequency reported by Warner (1979). As noted by Greene and Capella (1986), the nature of the task and the topic may have a major influence on the periodicity and frequency of the temporal cycles in fluency. The task used in our study was more similar to those used by Roberts and Kirsner (2000) and Merlo and Barbosa (2010) than by Warner (1979).

Furthermore, we developed a semi-automatic computerized method to measure four characteristics of temporal cycles in order to more specifically determine the relationship between temporal cycles and cognitive decline. Based on our findings, it appears that a higher mean frequency and lower r-index of temporal cycles in speech fluency may be associated with a diagnosis of FTLN, a neurodegenerative disorder known to cause cognitive decline. In the absence of additional studies in populations with other neurological diagnoses, we cannot say if this association is specific to FTLN; however, the fact that FTLN patients exhibited significant differences in temporal cycle characteristics from the subjects without a dementia diagnosis does provide evidence that temporal cycles are sensitive to cognitive decline associated with FTLN albeit not necessarily specific to FTLN. In addition, the g-statistic is associated with an established clinical measure of language impairment, indicating that periodic temporal cycles are more likely to be found in patients who are independently rated as sounding less linguistically impaired. Our findings also indicate that there is a measurable relationship between age and temporal cycles with respect to temporal cycle frequency mean and mode.

Our study also provides evidence to support the hypothesis that temporal cycles are constrained by the same cognitive resources that are affected by dementia and the natural aging process. While we cannot say definitively *which* cognitive resources are affected based on the current study, our findings, considered alongside other work on aging and dementia, are consistent with the effects of limitations in executive functioning and working memory (Caplan & Waters, 1996, 1999) due to deterioration of frontal brain networks (Farag, Troiani, Bonner, Powers, Avants, et al., 2010; Gorno-Tempini, Dronkers, Rankin, et al. 2004b; Mesulam, Weineke, Rogalski, Cobia, Thompson, et al., 2009; Price, 2000). Our findings indicate that the mean of temporal cycle frequency is higher in the FTLN group as compared to the controls and it is also higher in the older controls as compared to the younger controls. Conversely, we also observed that the r-index is lower (less volume at lower frequencies) in the FTLN group as compared to the controls; r-index was also lower in the older controls as compared to the younger controls. These observations indicate that dementia and aging tend to affect temporal cycles in fluency occurring at lower frequencies. Cognitive processes that manifest themselves in low frequency events tend to unfold over longer periods of time as compared to cognitive processes that manifest themselves via high

frequency events. For example, processes that take a long time to unfold such as macroplanning tend to require greater attention and executive control (Greene & Capella, 1986; Levelt, 1989). Thus, one possible implication of these findings is that aging and dementia have greater effects on the more conscious, less automatic processes and, therefore, are more clearly observable at the higher discourse level of language use. The latter assertion is supported by evidence from prior work by Ash et al., showing that all of FTLT groups in the study (bvFTD, PNFA and SD) exhibited discourse level impairments (Ash, Moore, Antani, McCawley, Work, et al., 2006).

While we did not find any significant differences in the measures of periodicity (r-index and g-statistic) among the four variants of FTLT, the g-statistic measure showed the lowest value for the PNFA group and the r-index showed the lowest value for the PLA group, which is consistent with the phenomenology of these two variants of FTLT. The PNFA variant is characterized by dysfluent, effortful and agrammatical speech (Ash, et al., 2008; Bird, et al., 2000; Gorno-Tempini, et al., 2004; Grossman, 2002; Peelle, et al., 2007; Weintraub, Rubin, & Mesulam, 1990). The PLA variant has been characterized by slower speaking rate, hesitations and pauses attributable to word finding pauses (Gorno-Tempini, et al., 2008). The most prevalent FTLT subgroup in our population consisted of patients with bvFTD (n=17), followed by the PNFA group (n=12). A recent study by Farag et al. (Farag, Troiani, Bonner, Powers, Avants, Gee, Grossman, 2010) found significant cortical atrophy in the inferior and dorsolateral frontal regions of the brain frontal areas of the brain bilaterally. Damage to the frontal cortex is associated with decreases in executive functioning and verbal working memory – that are also a large part of the phenomenology of the PNFA and bvFTD variants. Furthermore, fMRI studies of narrative speech production in healthy populations revealed that bilateral prefrontal and left temporal-parietal regions were activated during spoken picture descriptions (Troiani, Fernández-Seara, Wang, Detre, Ash, Grossman, 2008) and the left anterior insula, inferior frontal gyrus (a.k.a., Broca's area) and pre-motor cortex were activated during a sentence production task (Kemeny, Ye, Birn and Braun, 2005). Thus, our findings of reduced volume at low frequencies of temporal fluency cycles likely attributable to degradation of executive control and working memory in aging and dementia may have neuroanatomical correlates in frontal brain areas and/or progressive impairment of fronto-temporal interactions.

Section 5: Limitations

Several limitations must be acknowledged in order to facilitate the interpretation of the results of this study. First, the spontaneous speech elicitation tool used in this study is a picture description task. This is a limitation as the illustration was relatively simple and graphical support was constantly available throughout the task, which may have aided in macroplanning of subjects' speech and thus making their speech more regular than descriptions of a recent event, future plans, or family members (as in Roberts & Kirsner, 2000). However, having a picture description task as a speech elicitation tool is also a distinct strength from a methodological standpoint as it ensures that all subjects responded to exactly the same stimulus, which factors out variables such as the complexity of the events being recalled, their temporal distance from the present, or emotional associations with family members and events. Second, the older controls in our study represent a convenience sample from a nursing home population. To the best of our knowledge (based on nursing home records) these participants did not have a diagnosis of dementia; however, nursing home residents often suffer from depression and other illnesses that may have affected the results of this study. According to a clinical evaluation, all of our older control subjects were reported as showing no language production or comprehension impairment detected by the nursing home healthcare professionals. In addition, while over 80% of the nursing home residents that participated in this study had some depressive symptoms reported on the MDS

forms, all symptoms for all subjects were reported to be mild and easily altered. Third, the FTLT subgroups currently are relatively small and do not allow us to draw any definitive conclusions with respect to the relationship between temporal cycles and FTLT variants in this preliminary study. Future work will include larger samples. Fourth, all of our subjects were native speakers of North American English and all subjects completed the task in English. Therefore, the results of the current study are applicable only to native speakers of North American English but may be extended to other English variants and other languages in future studies.

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Figure 1. The “Henderson method” of plotting temporal cycles. Investigator judged where cycles started and ended; measurements of cycle length were then made by hand. (Data from one younger subject in our control sample.)

Figure 2.
The “Cookie Theft” picture description stimulus from the Boston Diagnostic Aphasia Examination.

Figure 3. Power spectra for: (a) a sine wave signal, (b) a randomly generated white noise signal, and (c) an actual fluency signal from one of our younger control subjects.

Figure 4. Averaged power spectra for FTLD and control groups, with the values of the mode and mean of the time series indicated with a vertical dotted line.

Figure 5. Averaged power spectra for the younger and older subgroups within the control group showing a shift in both mean and mode frequencies towards greater values for older.

Table 1

Spontaneous speech coding scheme.

Codes	Hesitations	Examples
T_	Breaths, coughs, tsks, other non-speech noises	
F_	Filled pauses	"um," "ah," "eh," "well"
S_	False starts, material to be subsequently repaired	"the da- (I mean the mom)"
R_	Repetitions/perseverations of words or ideas, except overt corrections of previous mispronunciations/circumlocutions	"she's washing- (um, she's washing the dishes)"
SIL	Silent pause	
Fluent speech		
C_	Circumlocutions	"the thing the water comes out of" (=faucet)
M_	Mispronunciations, neologisms	"chookie (ah, I mean cookie)"
P_	Parenthetical remarks, remarks directed toward examiner, remarks on experiment itself	"Is this what I'm supposed to be talking about?"
	All else	
Excluded from analysis		
E_	Speech by the examiner that administered the test	
	Initial and final pauses	

Table 2

Summary of results comparing FTL D and control groups.

	G-statistic	p	R-index	p	Mean	p	Mode	p
FTLD patients	0.187	0.608	0.360	0.039	0.036	0.001	0.0089	0.414
Healthy controls (young & old combined)	0.172		0.428		0.030		0.012	

Table 3

Summary of results comparing the four FTLD variant subgroups.

	G-statistic	p	R-index	p	Mean	p	Mode	p
bvFTD	0.174	0.58	0.376	0.31	0.037	0.11	0.016	0.13
PNFA	0.148		0.378		0.038		0.027	
PLA	0.165		0.253		0.038		0.027	
SD	0.157		0.369		0.032		0.014	
Correlation with CDRL (Spearman's rho)	-0.5	0.002	-0.05	0.79	0.03	0.89	0.03	0.88

Table 4

Summary of results comparing younger and older control subgroups.

	G-statistic	p	R-index	p	Mean	p	Mode	p
Older controls	0.119	0.177	0.396	0.041	0.032	0.036	0.026	0.035
Younger controls	0.157		0.472		0.027		0.016	
Correlation with Age (Spearman's rho)	0.31	0.189	0.25	0.29	-0.48	0.036	-0.46	0.047