Speech Planning Happens Before Speech Execution: Online Reaction Time Methods in the Study of Apraxia of Speech

Edwin Maas[a] and Marja-Liisa Mailend[a]

Purpose: The purpose of this article is to present an argument for the use of online reaction time (RT) methods to the study of apraxia of speech (AOS) and to review the existing small literature in this area and the contributions it has made to our fundamental understanding of speech planning (deficits) in AOS.
Method: Following a brief description of limitations of offline perceptual methods, we provide a narrative review of various types of RT paradigms from the (speech) motor programming and psycholinguistic literatures and their (thus far limited) application with AOS.
Conclusion: On the basis of the review of the literature, we conclude that with careful consideration of potential challenges and caveats, RT approaches hold great promise to advance our understanding of AOS, in particular with respect to the speech planning processes that generate the speech signal before initiation. A deeper understanding of the nature and time course of speech planning and its disruptions in AOS may enhance diagnosis and treatment for AOS.
Results: Only a handful of published studies on apraxia of speech have used reaction time methods. However, these studies have provided deeper insight into speech planning impairments in AOS based on a variety of experimental paradigms.

Key Words: apraxia of speech, motor programming, reaction time, speech production

Since the days of Fred Darley and his colleagues, apraxia of speech (AOS) has become established as a clinical disorder separate from aphasia on the one hand and from the dysarthrias on the other (Darley, Aronson, & Brown, 1975). A considerable body of research has been accumulated in the last 4 decades, and our understanding of AOS has seen significant advances. In current thinking, AOS is considered a disorder of speech motor planning and/or programming (e.g., Ballard, Granier, & Robin, 2000; Code, 1998; Deger & Ziegler, 2002; Duffy, 2005; Maas, Robin, Wright, & Ballard, 2008; McNeil, Robin, & Schmidt, 2009; Van der Merwe, 2009). Both the clinical diagnosis of AOS and much of the research base is based on perceptual analysis of speech output in a variety of contexts (Wambaugh, Duffy, McNeil, Robin, & Rogers, 2006). Although this approach is clearly valuable (e.g., Aichert & Ziegler, 2004), there are well-known limitations of this method. The present article presents an argument for supplementing offline perceptual analyses with online reaction time (RT) measures. The crux of the argument is that speech planning occurs before speech execution, and as such it may be critical to obtain more direct, online measures of the processes occurring during, rather than after, the planning stage.

The remainder of the article is organized as follows. First, we present a brief statement of the problem(s) with perceptual analysis as a methodology to study speech planning. Second, we discuss the potential value of more online RT methods developed in the motor programming and psycholinguistic literatures by reviewing the limited number of published studies and some recent work from our laboratory and by identifying several promising directions for further research using such methods to study AOS. Finally, we highlight some challenges and considerations in using RT methods with speakers with AOS.

[a]University of Arizona, Tucson
Correspondence to Edwin Maas: emaas@email.arizona.edu
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Statement of Problem: Limitations of Perceptual Analysis

Although the limitations of perceptual analysis have been recognized for some time (e.g., Kent, 1996; MacNeilage, 1982; A. S. Meyer, 1992), it is helpful to review some of these limitations to set the stage for our argument for using RT methods.

One obvious limitation is that our speech perception is highly categorical (e.g., Liberman, Harris, Hoffman, & Griffith, 1957; cf. Kent, 1996). A consequence of categorical perception is that listeners are more likely to perceive substitutions (which cross phoneme boundaries) than distortions (which involve within-phoneme abnormalities) or to perceive distortions as correct productions. Although studies with narrow transcription methods have produced evidence that speakers with AOS produce speech sound distortions (e.g., Odell, McNeil, Rosenbek, & Hunter, 1990), such analyses are time consuming and require highly trained listeners and high-quality recordings. Obtaining acceptable reliability between transcribers is also not a trivial challenge.

A second, related, limitation is the low sensitivity for speakers with mild AOS, who may produce a relatively small number of (certain types of) errors. Low numbers of errors available for statistical, quantitative, and qualitative analysis may require larger sample sizes of participants and/or trials. Similarly, unimpaired control speakers generally do not produce errors (i.e., are at ceiling with near-zero variance), which complicates comparisons of impairments on different tasks (e.g., reading vs. repetition) within an individual case. It might be of theoretical or clinical interest to determine whether a given patient demonstrates a dissociation in performance between different tasks or conditions (e.g., reading vs. repetition; short vs. long words) compared with unimpaired control speakers. Merely demonstrating a difference between tasks within a given patient[1] does not address the question of whether this difference is abnormally large or small (cf. Crawford & Garthwaite, 2007; Crawford, Garthwaite, & Gray, 2003)—that is, whether there is a main effect or an interaction. It could be that a task difference is normal in the control population but not reflected in accuracy measures. Methods are available to establish presence and severity of impairments and dissociations in reference to a control sample (e.g., Crawford & Garthwaite, 2007), but these methods require that there be variance in the control sample to estimate the degree of impairment on each task. Thus, ceiling or floor effects, which are likely for control speakers when using accuracy or error rate measures, are problematic (Crawford et al., 2003) because they limit the ability to examine interactions.

Third, analysis of speech error patterns does not provide information about perceptually adequate speech. That is, speech errors reflect "derailments of the process" (Levelt, Roelofs, & Meyer, 1999, p. 2) rather than the process as it functions when no overt, perceptible errors are produced. Although errors are certainly of interest in the case of speech disorders, important information about the process of speech planning may be overlooked when focusing exclusively on observable errors.

Finally, the perceptual error analysis method is based on the final speech output, which represents the cumulative product of a series of planning stages (cf. Rogers, Redmond, & Alarcon, 1999). In error analysis, there is generally little consideration of the time course of the various processing stages involved in generating the final output. Although there are exceptions in which different planning stages are distinguished in a sequential sense (e.g., Den Ouden, 2002; Garrett, 1975; Shattuck-Hufnagel, 1983), more detailed information about time course of speech planning is generally impossible to obtain (A. S. Meyer, 1992).

Together, these limitations may lead to confusion regarding the apraxic versus phonological versus dysarthric nature of the underlying pathomechanism. There are several alternative methodological approaches that circumvent or minimize some of these limitations. For example, the use of acoustic or physiologic analysis methods minimizes the categorical perception problem as well as the small-number-of-errors problem because such measures are continuous and can be performed on perceptually accurate speech as well as on speech errors. Important contributions to the understanding of AOS have been made using acoustic (e.g., Buchwald & Miozzo, 2011; Collins, Rosenbek, & Wertz, 1983; Jacks, 2008; Kent & Rosenbek, 1983; Rogers, 1997; Seddoh et al., 1996; Ziegler & von Cramon, 1986) and physiologic (e.g., Bartle-Meyer, Goozée, & Murdoch, 2009; Hough & Klich, 1998; Itoh, Sasanuma, Hirose, Yoshioka, & Ushijima, 1980; Katz, Machetanz, Orth, & Schönle, 1990; Shankweiler, Harris, & Taylor, 1968; Sugishita et al., 1987) measures. Continued pursuit of these methodologies is likely to uncover more insights regarding AOS, especially when driven by detailed speech planning models (e.g., Maas, Mailend, & Guenther, 2012). However, acoustic and physiologic measures do share with perceptual measures the limitation that they are based on the final speech output, and as such do not tap directly into the unfolding speech planning process. If we are to take current models of speech planning seriously, we ought to attempt to tap the various proposed processing stages in a more direct manner.

[1]This task is in itself complicated because many within-participants statistical analyses require independent observations and assume normal distributions, which often is not the case in single-case analyses (Crawford, Garthwaite, & Gray, 2003).

Two types of methodologies that can generate information about the planning processes occurring prior to speech onset are neuroimaging methods with high temporal resolution—such as event-related potentials (ERPs; e.g., Costa, Strijkers, Martin, & Thierry, 2009; Laganaro, Morand, Michel, Spinelli, & Schnider, 2010; Laganaro, Morand, & Schnider, 2009) and magnetoencephalography (MEG; e.g., Houde, Nagarajan, Sekihara, & Merzenich, 2002; Levelt, Praamstra, Meyer, Helenius, & Salmelin, 1998)—and behavioral chronometric (RT) methods (e.g., Cholin, Dell, & Levelt, 2011). To the best of our knowledge, ERPs and MEG have not been used to study AOS specifically, probably because of the significant challenges involved, such as movement artifacts (e.g., Costa et al., 2009; Ganushchak, Christoffels, & Schiller, 2011; Hagoort & van Turennout, 1997). Although these challenges may not be insurmountable (see Ganushchak et al., 2011, for a recent review and methodological recommendations) and methods such as ERP and MEG hold promise for a greater understanding of online speech planning in AOS (cf. Laganaro et al., 2010, 2009, for application to aphasia), the present review focuses on RT methods because there is an existing literature, albeit a small one, that has employed RT methods to study AOS. In the next section, we review these RT studies, discuss their contributions to the understanding of AOS, and identify potentially fruitful directions for further research along these lines.

RT Paradigms to Study Speech Planning in AOS

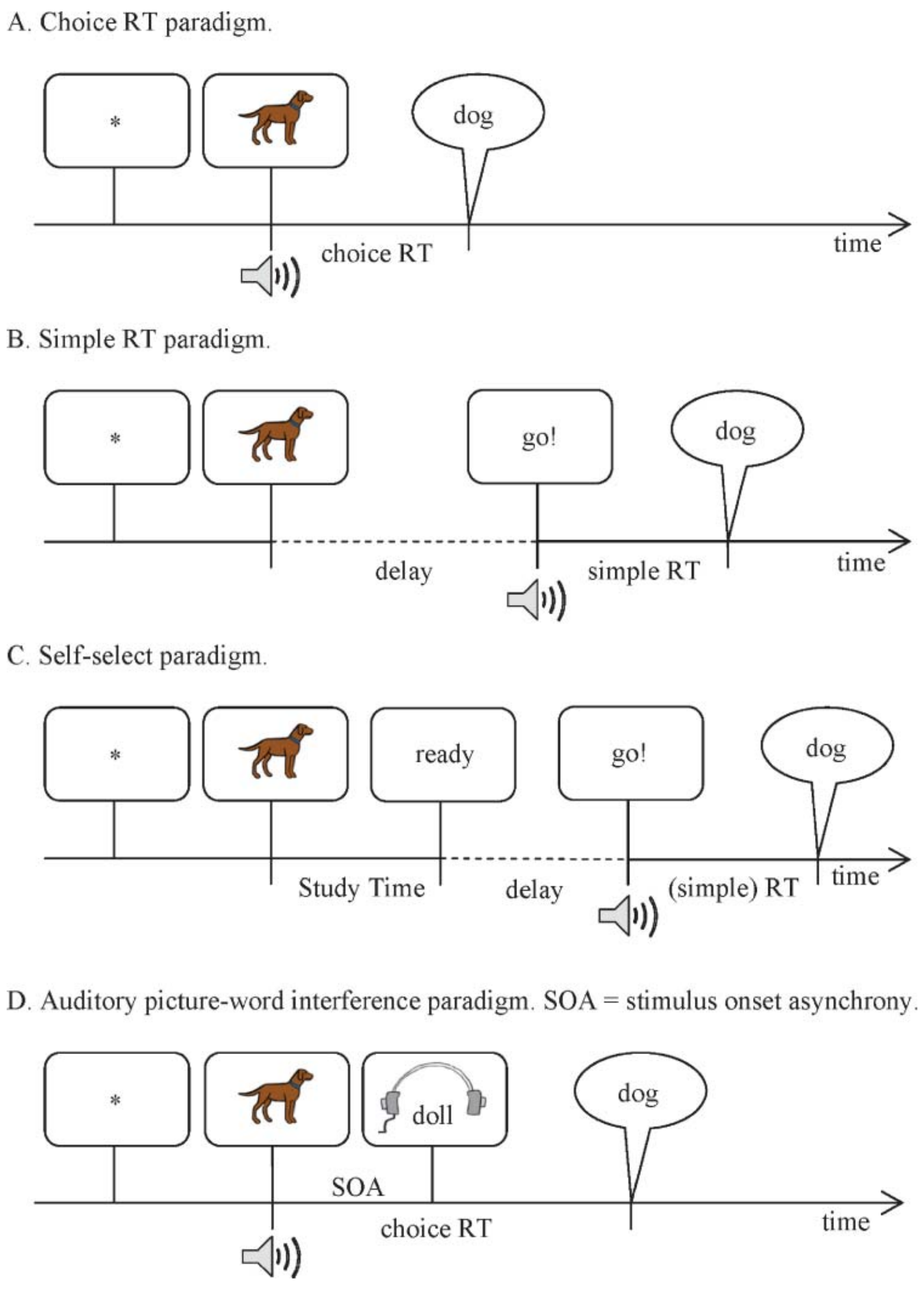
RT measures may provide important clues about the underlying nature of the deficit. Over the last 2 decades, the psycholinguistic production literature has moved toward a greater use of RT measures to better understand the details of the production process, and there appears to be general agreement that speech planning involves a number of sequentially ordered planning stages (for reviews, see Goldrick, 2006; Levelt, 1999). The argument formulated here is that the disordered production literature may similarly benefit from the use of RT measures to supplement information obtained from error analysis. Although this idea is by no means novel (e.g., Rogers et al., 1999; Towne & Crary, 1988; Ziegler, 2002), and in fact is incorporated in a widely used apraxia test (Dabul, 2000), there have been relatively few attempts in the literature to apply RT methods to the study of AOS. There is a considerable variety and flexibility of RT methods, including simple versus choice RT paradigms and interference and priming paradigms. Below, we briefly review these paradigms and their application to the study of AOS.

Simple and Choice RT Paradigms

Figure 1 depicts an overview of a choice RT paradigm (see Panel A) and a simple RT paradigm (see Panel B). In essence, the choice (immediate) RT paradigm requires the participant to respond immediately (i.e., make a choice between alternative possible responses and program the response). Thus, the RT measure (time between tone/picture and response onset; see Figure 1A) captures all intervening processes between stimulus presentation and response onset, including visual processing (in the case of picture naming or reading), object recognition, lexical retrieval, phonological planning, and motor planning. By contrast, the simple (delayed) RT paradigm allows the participant time to select and prepare the response in advance before a go-signal (e.g., a tone) cues the response. The simple RT measure therefore does not include visual processing, lexical retrieval, and so forth, but it captures later-occurring processes such as motor planning (e.g., Sternberg, Monsell, Knoll, & Wright, 1978). Thus, both paradigms may be used to capture aspects of motor planning. In both paradigms, the basic logic is that longer RT indicates additional processing, and the researcher's task is to implement careful experimental manipulations that are presumed to increase the processing load for a particular processing stage.

Although there has been debate in the motor literature about what sorts of preparation processes are captured in each of these paradigms (e.g., Klapp et al., 1979; Marteniuk & MacKenzie, 1981; Rosenbaum, 1980; Sternberg et al., 1978), more recently Klapp (1995, 2003) proposed a model of motor programming based on a synthesis of the findings from both paradigms. Briefly, this model decomposes motor programming into two stages: one called INT, which prepares the *int*ernal spatial and temporal properties of a given motor program, and one called SEQ, which is responsible for retrieving and unpacking the motor programs in their correct *seq*uence from a buffer. INT processing load depends on the complexity of a single motor program, whereas SEQ processing load depends on the number of motor programs. In this view, a comparison between simple and choice RT findings for a given manipulation (e.g., number of phonemes, number of syllables) can provide information about the size of motor plans, as explained further below. The supposition is that INT can be preprogrammed, whereas SEQ cannot. Because in a choice RT paradigm there is no opportunity to preprogram the response, any differential load on the INT process as a function of motor program complexity (e.g., duration, syllable structure) should be reflected in RT. If the response is initiated as soon as the first motor program is ready, then there should be no RT effect of the number of motor programs.

Figure 1. Schematic outlines of reaction time (RT) paradigms. The speaker icon indicates a go-signal tone.



In a simple RT task, the participant can prepare the response and then must hold on to it in a motor buffer until the go-signal appears. At the go-signal, the first motor program must be selected and retrieved from the buffer, and the amount of time it takes to retrieve a program from the buffer depends on the number of programs residing in the buffer. Although the order of motor programs is likely specified in some type of abstract timing frame (Klapp, 2003) to prevent serial order errors, simple RT reveals sequence length effects even when the order is known in advance (e.g., Klapp, 2003; Sternberg et al., 1978). This indicates that the individual motor programs that fill the slots in the timing frame are represented separately from the frame and that the SEQ process must still scan the buffer to find the right program at the right time. Thus, in this view, simple RT reflects the SEQ (buffer scanning and retrieval) process but not the INT process (because that has been preprogrammed during the delay). If a particular experimental manipulation affects simple RT but not choice RT (e.g., longer simple RT with increasing number of syllables, regardless of syllable complexity), this would suggest that this manipulation reflects the number of motor programs (e.g., syllables in this case). If a particular manipulation affects choice RT (e.g., longer choice RT for CCVCC than CVC syllables) but not simple RT, then this would suggest that syllable structure reflects the complexity of a single (syllable-sized) motor program rather than a sequence of segment-sized units.

With respect to AOS, Deal and Darley (1972) were the first to specifically include RT measures. They compared RT for reading a list of words with either no delay (i.e., choice RT) or with a delay of 3 or 6 s (i.e., simple RT). They reported longer RTs for the AOS group overall as measured with a stopwatch, but they did not report the data as a function of delay interval. Another early study that applied RT methods to investigate AOS was reported by Towne and Crary (1988). They compared a patient with AOS to two patients with fluent aphasia and to unimpaired control speakers, in both a choice RT paradigm and in a simple RT paradigm, using monosyllabic words starting with bilabial plosives. They used electromyography (EMG) to fractionate the total RT into a premotor RT (time between go-signal[2] and EMG onset) and a motor RT (time between EMG onset and onset of audible speech). The speaker with AOS showed longer premotor RT than unimpaired control speakers in the choice RT task but not in the simple RT task, whereas there were no RT differences between the aphasic and control speakers. Furthermore, Towne and Crary noted that the motor RT in both paradigms was longer for incorrect responses than for correct responses for the speaker with AOS but not for the aphasic speakers. Towne and Crary suggested that the longer choice RT, even for correct responses, may indicate a disruption of the ability to rapidly plan the correct speech initiation commands. Relative to the INT/SEQ model, these findings suggest that the problem for this speaker with AOS resided in the INT process rather than in the SEQ process.

Using a simple RT paradigm, Deger and Ziegler (2002) provided further support for the notion of an INT deficit in AOS. They examined simple RT as a function of sequence length for nonword sequences consisting of repeated syllables (*dada* vs. *dadada*) and as a function of sequence complexity defined in terms of number of different syllables (*dada* vs. *daba*). These manipulations were designed to tax the SEQ and the INT processes, respectively. Deger and Ziegler found that control speakers and speakers with aphasia but no AOS showed a sequence length effect, with longer RT for *dadada* than for *dada,* but no sequence complexity effect (*dada* = *daba*). This pattern suggests that the two-syllable sequences were integrated into single motor programs, and as such did not differ in their SEQ load, whereas the three-syllable sequences were composed of multiple motor programs, thus increasing the SEQ load. In contrast, despite comparable RTs in the *dada* condition, the speakers with AOS showed no sequence length effect but instead showed a sequence complexity effect on RT. Deger and Ziegler concluded that speakers with AOS may have a particular difficulty in integrating different syllables into a single motor program. They further argued that these findings provide evidence against the notion of a buffer capacity restriction to a single syllable as proposed by Rogers and Storkel (1999) because the longer RT for *daba* compared with *dada* indicates that more than one syllable resided in the buffer.

Additional support for the notion of an INT deficit in AOS was provided by Maas et al. (2008). This study used a self-select paradigm (see Figure 1C) in which participants are given time to prepare their response and indicate when they are ready before a go-signal. This paradigm differs from the simple RT paradigm primarily in the fact that the duration of the preparation stage is measured, thus providing a more direct measure of both INT and SEQ on a single trial (INT reflected in Study Time, SEQ reflected in RT). Their targets consisted of mono-syllabic and four-syllabic utterances involving the syllable *ba* with different durations, creating different temporal-prosodic patterns. The findings revealed longer Study Time for speakers with AOS but not for speakers with aphasia without AOS. There were no group differences for RT. Sequence length effects were evident on Study Time rather than RT, suggesting that the sequences of four syllables were integrated into single motor programs, perhaps because of the temporal-prosodic patterns imposed by the targets. These findings further corroborate those of Towne and Crary (1988) and Deger and Ziegler (2002) in supporting the notion of a deficit in preprogramming (INT) but not in the SEQ process.

To summarize thus far, these basic RT approaches (choice and simple RT paradigms) provide some degree of continuity with the basic motor programming literature that is based on these paradigms, and they facilitate the framing of AOS in terms of motor programming models. Though there are few RT studies with speakers with AOS, the simple and choice RT paradigms are promising for providing a clearer delineation of motor programming deficits in AOS. First, these paradigms enable separation of (impairments to) specific motor programming stages (Deger & Ziegler, 2002; Maas et al., 2008; Towne & Crary, 1988). Second, they enable investigation of relationships between accuracy and RT (e.g., longer RTs

[2]Towne and Crary (1988) included an auditory tone as a go-signal in both the simple RT task and in the choice RT task (i.e., tone was presented simultaneously with word onset to indicate that an immediate response was required, similar to Figure 1A).

for incorrect responses; Towne & Crary, 1988). Third, they permit identification of what constitute planning units (e.g., syllables or syllable sequences; Deger & Ziegler, 2002; Maas et al., 2008) by comparing the effects of a given experimental manipulation on simple RT and choice RT. In this context, it is interesting to note that RT evidence from the limb motor learning literature indicates that certain practice schedules (i.e., random practice) result in formation of motor "chunks" of fingertap sequences, unlike other schedules (i.e., blocked practice; e.g., Klapp, 1995; Wright, Black, Immink, Brueckner, & Magnuson, 2004). This line of work may be relevant for speech motor learning in AOS, especially considering the promising findings of enhanced learning with random practice in AOS treatment (Knock, Ballard, Robin, & Schmidt, 2000). RT measures may provide a means to assess the integration or "chunking" of speech utterances as learning progresses, or as a function of different prosodic or articulatory properties of the utterances.

Up to this point, we have discussed studies in which the primary manipulated factors are the target properties (e.g., sequence length, complexity). However, other, more sophisticated, paradigms have been used in the motor programming literature and the psycholinguistic production literature, as we discuss next.

Priming and Interference Paradigms

One of the challenges in using choice and simple RT paradigms, in which the primary manipulated factors are response properties such as sequence length or complexity, is that this approach involves comparisons between different responses, which may make it difficult to disentangle potential confounds. For example, in the comparison between short and long syllable sequences, there is not only a difference in motor programming demands but there is also additional phonological processing involved for the longer sequences. Although arguments can be made to support a motoric versus phonological account of observed effects, another approach is to compare RT with the same targets under different conditions. A variety of paradigms exist in this general category, including different types of priming paradigms developed in the psycholinguistic literature.

One widely used priming paradigm is the picture–word interference task, which has a visual and an auditory variant (e.g., A. S. Meyer & Schriefers, 1991; Schriefers, Meyer, & Levelt, 1990). In the typical version of this paradigm (see Figure 1D), speakers produce target words in a choice RT task while hearing a distracter word just prior to speech onset. The distracter is thought to influence the ongoing speech planning processes and, thus, systematic manipulation of the timing and relationship between distracter and target offers a window into speech planning in real time. Using this type of task, studies with unimpaired speakers have revealed information about the time course of semantic and phonological planning and have shown that phonological planning involves a serial left-to-right process operating on subsyllabic units. For example, A. S. Meyer and Schriefers (1991) observed faster RTs (priming) for target words when speakers heard a distracter word with the same onset and vowel (e.g., hearing *doll* while planning to say *dog*) than when they heard distracters with a different onset and vowel (e.g., hearing *cup* while planning to say *dog*). Furthermore, this priming effect occurred earlier for words with initial overlap (as in the preceding example) than for words with final overlap (e.g., hearing *fog* vs. *cup* while planning to say *dog*), suggesting a serial process of encoding subsyllabic units (A. S. Meyer & Schriefers, 1991).

These priming effects have been replicated (e.g., Damian, 2003), including for single-segment overlap (Ventura, Kolinsky, Querido, Fernandes, & Morais, 2007), and variants of this paradigm have begun to be extended to study other populations, including typically developing children (e.g., Brooks & MacWhinney, 2000; Seiger-Gardner & Schwartz, 2008), children with speech or language disorders (e.g., Byrd, Conture, & Ohde, 2007; Seiger-Gardner & Brooks, 2008), and adults with aphasia (e.g., Hashimoto & Thompson, 2010; Wilshire, Keall, Stuart, & O'Donnell, 2007; Wunderlich & Ziegler, 2011). However, to the best of our knowledge, there has been only one published report that applied this paradigm specifically to the study of AOS (Rogers et al., 1999).

Rogers et al. (1999) examined the effects of auditorily presented semantic and phonological distracters (vs. a no-distracter condition) on picture naming RT in speakers with AOS, speakers with aphasia but without AOS, and age-matched control speakers. They used a wide range of stimulus-onset asynchronies (time between distracter onset and picture onset), and they examined the onset and offset of interference effects compared with the no-distracter condition. They noted that in speakers with AOS, the period of semantic interference was prolonged, and the peak phonological interference effect was delayed, compared both with unimpaired speakers and with aphasic speakers. On the basis of their results, Rogers et al. hypothesized that the activation of phonological information is protracted in speakers with AOS and that this delay in accessing the phonological form of a word may in part explain the initiation difficulties and slow speech rate observed in AOS. Such delays in phonological activation may also play a causative or exacerbating role in the speech motor planning difficulties in AOS.

Although the hypothesis of a phonological activation impairment in AOS is intriguing and underscores the potential value of the picture–word interference paradigm in the investigation of AOS, the lack of an unrelated distracter baseline condition in Rogers et al.'s (1999) study complicates the interpretation of the findings (i.e., the findings indicate interference but not facilitation). Thus, these findings deserve follow-up in future studies, with additional manipulations to further specify the nature of such putative phonological planning difficulties. For example, the use of feature priming (e.g., *top–doll*) might reveal information about the nature of phonological representations. This in turn may inform decisions about selecting optimal treatment targets (e.g., contrastive pairs). Knowledge about the temporal windows in which different planning stages and disruptions occur may enable targeting specific processes or stages in treatment, for example, by presenting various types of cues at the optimal time (cf. Wunderlich & Ziegler, 2011).

A different type of priming paradigm is the preparation priming paradigm (or implicit priming paradigm; e.g., A. S. Meyer, 1990). This paradigm is akin to the partial precue paradigm developed in the motor programming literature to examine the hierarchical and temporal organization of motor programming (e.g., Klapp, 2003; Rosenbaum, 1980; Wright, Magnuson, & Black, 2005; Zelaznik, 1981). In a partial precue paradigm, individuals are given partial advance information about the upcoming movement (e.g., direction of movement, left vs. right hand), and RT is compared with situations in which such advance information is not available (e.g., no information about direction and hand). Reductions in RT with advance information about a particular movement parameter are taken to mean that this movement parameter can be programmed in advance, independent from other movement parameters. Conversely, if such independent preprogramming is not possible (i.e., no reduction in RT), the motor programming process may be hierarchical in nature, such that specification of one movement parameter can only be completed once another movement parameter has been specified. Thus, by comparing patterns of RT reductions for different movement parameters, inferences can be made about the independence or serial organization of programming different aspects of a movement (Rosenbaum, 1980; Zelaznik, 1981).

Applications of the preparation priming paradigm to speech planning typically involve grouping a set of targets by some phonological property, such as initial segment or syllable (e.g., Damian, 2003; A. S. Meyer, 1990; Roelofs, 1999; Roelofs & Meyer, 1998). For example, choice RT to *dog* is compared when it occurs in a set with words such as *dune* and *dish* versus when it occurs in a set with unrelated words such as *pool* and *ship*. Findings from these studies have revealed that initial segments (but not final segments) can be prepared in advance as long as the number of syllables and stress pattern is also shared (Damian, 2003; A. S. Meyer, 1990; Roelofs & Meyer, 1998). No priming is observed when only the initial segment or only the number of syllables and stress pattern is shared, suggesting that these information types are retrieved separately and in approximately the same amount of time (Roelofs & Meyer, 1998). In addition, no priming is observed when one of the words in the shared set differs by a single feature (e.g., *dog–tune–dish*; Roelofs, 1999), suggesting that the preparation effect involves phoneme-sized units rather than articulatory gestures, at least in unimpaired speakers.

To the best of our knowledge, there are no studies that have extended this paradigm to the study of speakers with AOS, with the exception of some recent work from our laboratory (Gutiérrez, Maas, & Ballard, 2011). In this study, we followed-up on the hypothesis proposed by Rogers et al. (1999) regarding the slow activation of phonological information in AOS. We systematically varied the nature of phonological overlap (segment, frame,[3] segment + frame) to further examine which type of phonological information, if any, is slow to activate in AOS. Although no clear systematic patterns were evident in the error rates (consistent with findings by Mauszycki, Wambaugh, & Cameron, 2010a, 2010b), the RT analyses indicated that speakers with AOS may have difficulty activating segmental information, thus supporting and further refining Rogers et al.'s hypothesis.

Finally, there are other RT paradigms that have been used successfully to investigate speech motor programming but that have not yet been explored with AOS, including the reprogramming task (e.g., D. E. Meyer & Gordon, 1985; Rogers & Storkel, 1998; Spencer & Rogers, 2005; Spencer & Wiley, 2008). For instance, Spencer and Rogers (2005) varied short and long delays in a simple RT task and combined this with a switch condition in which the go-signal specified a different response, requiring clearing and reprogramming of the buffer. The degree of interference (*switch cost*; Spencer & Wiley, 2008) depends on the timing and relation between prepared and required response, and it provides information about the speech planning process at different points in time. On the basis of the RT patterns, Spencer and Rogers suggested that speakers with hypokinetic dysarthria had difficulties with maintaining and switching motor programs, whereas speakers with ataxic dysarthria had difficulties with preprogramming. Although this paradigm has not yet been extended to the study of AOS, and it remains to be seen whether this paradigm is feasible with speakers with AOS, the findings of Spencer and Rogers do suggest that much can be gained from exploring this paradigm in AOS.

In sum, although preliminary, the findings reviewed above support the potential utility of these various priming

[3]*Frame*, in this case, refers to the metrical frame as defined by Levelt et al. (1999), which specifies the number of syllables and the stress pattern.

paradigms to enhance our understanding of AOS. Future studies with these paradigms can provide information about the integrity, nature, and time course of speech planning in AOS. For example, by examining different types of overlap (e.g., suprasegmental, featural), one might gain further insight into which parts of a speech plan can be prepared and activated independently and which ones cannot.

With respect to clinical implications, the ability to establish and characterize phonological impairments in AOS may inform treatment decisions. The presence of a phonological impairment may call for a different set of optimal treatment targets, cues, or practice conditions. For example, Wambaugh, Martinez, McNeil, and Rogers (1999) observed unwanted overgeneralization of treatment in a speaker with AOS and aphasia when using target sets blocked by initial sound (e.g., *pie, pear, puck*; *key, car, cab*) but not when using sets with different initial sounds (e.g., *pie, car, shell*), suggesting the importance of including contrastive targets for this patient. Wambaugh et al. urged future studies to "elucidate the role that subject characteristics and treatment parameters play in the generation of the overgeneralization effect" (p. 834). The presence and/or nature of phonological deficits may be an important participant characteristic that helps explain and predict whether overgeneralization is likely to occur. In a similar vein, evidence from the aphasia literature suggests that different underlying naming deficits produce distinct patterns of treatment effects relative to interference or facilitation from target sets with overlap (cf. Martin, Fink, & Laine, 2004). Clearly, much more research is needed in both basic understanding and in treatment of AOS to determine whether short-term effects on experimental tasks have predictive value for longer term treatment outcomes. The ability to assess phonological encoding more or less independently from speech motor planning deficits may be important in this respect. The utility and feasibility of using RT paradigms in routine clinical practice will naturally require further exploration. Perhaps once the utility of such paradigms has been robustly established, a clinically feasible standardized task can be developed, with normative data to aid in interpretation. At present, the value of these RT approaches lies primarily in enhancing our basic understanding of the nature and time course of speech planning in AOS.

Challenges in Applying RT Methods to Study AOS

Thus far, we have formulated the argument that supplementing the methodological armamentarium with various RT methods has potential to advance our understanding of speech planning processes and impairments in AOS, and we have reviewed initial attempts in this direction to bolster this argument. However, despite the potential added value of RT methods, we certainly do not wish to suggest that RT paradigms are a panacea for all questions relating to AOS. As with any single method, there are of course also limitations to RT methods. Below, we briefly discuss some of these limitations.

A first limitation is that even RT approaches require some degree of perceptual judgment of accuracy, for example, to determine which responses should be included in the RT analysis. Thus, categorical perception still plays a role, albeit a more limited one than in error analyses. Depending on the number of errors, RT analyses as a function of accuracy may also be informative (e.g., Towne & Crary, 1988). The procedure of rerunning incorrect trials provides a way to maximize the number of correct trials for analysis and still preserves the ability to analyze incorrect trials (perceptually as well as in terms of RT).

Second, these methods may not be suitable for individuals with severe AOS and instead may be restricted to mild to moderate cases. In a certain sense, this is the opposite problem of the speech error approach, which may not be suitable for speakers with mild AOS who make very few errors but which may be informative and appropriate for speakers with severe AOS. Associated impairments must also be taken into consideration, such as severity of naming deficits, reading ability (if using written stimuli), and attentional and sensory impairments that may interfere with stimulus processing or response selection. Thus, patient characteristics place important limits on generalizability. However, with creative adaptation of experimental procedures and appropriately restricted scope of generalization, the manipulations derived from models and methods of motor programming may nevertheless prove informative, even if expressed in error rate rather than RT for severe cases. Examples of modifications of experimental procedures to minimize the effects of some of these concomitant impairments include the use of different (or multiple) stimulus presentation modalities depending on a participant's strengths (e.g., written stimuli, picture stimuli), familiarization with the targets to maximize the number of correct responses (e.g., Deger & Ziegler, 2002; Gutiérrez et al., 2011; Maas et al., 2008; Towne & Crary, 1988; Wunderlich & Ziegler, 2011), inclusion of additional trials or sessions to account for increased variability (e.g., Deger & Ziegler, 2002), inclusion of frequent rest breaks or shorter sessions to minimize fatigue and reduced attention (e.g., Gutiérrez et al., 2011; Maas et al., 2008), keeping the number of response alternatives (set size) small and constant to account for possible executive function difficulties (e.g., Deger & Ziegler, 2002; Gutiérrez et al., 2011), and rerunning incorrect trials to obtain a maximal number of correct responses (e.g., Gutiérrez et al., 2011; Maas et al., 2008).

A third challenge lies in the careful control and measurement involved in conducting this type of research. To obtain reliable RT effects, often specialized software and recording equipment are needed for stimulus presentation and response collection. Measurements based on stopwatch responses from the examiner (e.g., Dabul, 2000; Deal & Darley, 1972) or from offset of a spoken model (Varley, Whiteside, Hammill, & Cooper, 2006; Varley, Whiteside, & Luff, 1999) are unlikely to be reliable, sufficiently precise, or valid (cf. Ziegler, 2001). For example, participants may start planning their response during the spoken model, and measurement from the onset or offset of the model does not take into account the duration of the model (and thus how much planning the participant had already completed during the model). Similarly, the results from voicekey mechanisms are not always valid (e.g., because of lip smacks, soft voice), thus requiring a considerable time investment to obtain RTs from the acoustic record (and inclusion of a tone to mark the onset of the RT interval; e.g., Maas et al., 2012). Patients also have to be instructed to respond as fast as possible, which may be more difficult for some patients than others.

Fourth, RT studies typically rely on comparisons of group means, on the basis of the assumption of a homogeneous population (e.g., college students). If one attempts to use group designs to study AOS, care must be taken to obtain relatively homogeneous groups (e.g., strict inclusion criteria) and perhaps larger sample sizes and/or larger numbers of trials because of the potential for increased variability in patient groups compared with unimpaired speakers. It is important to note however that this limitation is shared with other approaches such as perceptual error analyses, and the advantage of RT methods over such methods is that the control group is less likely to show ceiling effects in RT measures than in accuracy measures. Thus, comparisons of patterns across conditions (e.g., high-frequency vs. low-frequency words; monosyllabic vs. disyllabic words) are often impossible with error analysis (unless one has very large control groups). RT measures are more likely to enable detection of disproportionate difficulties in one condition over another compared with control speakers because RT measures provide an estimate of variance in the control group. Moreover, the sample size and homogeneity concern is not relevant when performing individual subject analyses such as those developed by Crawford and colleagues (e.g., Crawford & Garthwaite, 2007). In these types of analyses, each individual patient is compared with a normative control sample rather than being analyzed as a group. Although such analyses can be applied to perceptual error data, the ceiling effects in control speakers may still be a concern for those measures, unlike the RT measures, because these analyses require variance in the control data.

Finally, the interpretation of findings hinges on the interpretation of the experimental manipulation, and thus, independent sources of evidence are necessary to triangulate the nature of a disorder. For instance, if a speaker with AOS showed a disproportionate effect of a particular manipulation (e.g., disproportionate complexity effect), or abnormal priming patterns, additional argumentation is needed to claim that this reflects motor programming rather than phonological deficits or vice versa, because of potential confounds. This holds true for any experiment regardless of outcome measure and requires careful consideration of and control for confounds. The advantage of RT paradigms is that they enable some degree of cross-validation against an independent body of evidence based on unimpaired speakers. For example, the claim that an auditorily presented distracter word activates phonological segments on the output side is based independently on external evidence from the psycholinguistic production literature with unimpaired speakers. Although it is conceivable that the speech planning disruptions in AOS alter the interpretation of experimental manipulations, it seems reasonable to assume similar interpretations for similar effects (e.g., priming effects in AOS also signify phonological encoding).

In sum, research using RT paradigms to investigate AOS faces a number of challenges. However, many of these limitations are tractable with careful design and limitations of scope of generalization. Similar limitations exist with other methods, and the potential benefits for our understanding of AOS may outweigh these limitations. Ultimately, many different approaches will be needed to arrive at a complete understanding of AOS and speech planning in general. The argument here is that RT methods should be included given their strengths and potential to elucidate the nature of speech planning and its disruptions in AOS.

Conclusions

In this article, we argued for the potential value of RT methods for the fundamental understanding of AOS. This review suggests that the simple and choice RT methods may be particularly helpful in separating types of motor planning processes and in identifying planning "chunks," for example, whether a multisyllabic sequence is planned as a series or as a single integrated chunk. The priming RT methods appear particularly useful in assessing the integrity and time course of phonological planning and the structure and content of speech plans, for example, whether or how suprasegmental information is represented and used during speech planning. Although application to AOS has been rather limited to date, further developments with these paradigms are likely to deepen our understanding of AOS, which may help inform diagnosis of and treatment decisions for AOS and aphasia.

A full understanding of all aspects of AOS and speech planning in general will naturally require a combination of a range of methodologies (e.g., speech error analysis, acoustic and physiologic measures, computational modeling, and neuroimaging methods such as ERP and MEG). Despite the challenges and limitations reviewed above, with careful experimental design and control these various RT methods (a) minimize influences of categorical perception, (b) enable comparisons with unimpaired speakers to determine dissociations in performance, and (c) provide a real-time window into the ongoing speech planning process.

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