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Speech motor control in fluent and dysfluent speech production of an individual with apraxia of
speech and Broca's aphasia

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Abstract

In this study, movement data from lips, jaw and tongue were acquired using the AG-100 EMMA system from a relatively young individual with apraxia of speech (AOS) and Broca's aphasia. Two different analyses were performed. In the first analysis, kinematic and coordination data from error-free fluent speech samples were compared to the same type of data from a group of six age-matched control speakers (males & females). In the second analysis, selected movement data from the subject's fluent speech were compared to her dysfluent speech samples to gain more insight into potential underlying speech motor control mechanisms. Overall, the findings indicated that the subject with AOS and Broca's aphasia was very similar to her age matched controls with respect to fluent speech kinematics. However, in comparing different utterances, specific differences in movement characteristics were identified, especially for upper lip movements and lip coordination. Comparing these results from the fluent speech samples with the changes in gestural motion and coordination for dysfluent speech, the fluent speech characteristics suggest the use of compensatory motor control strategies. In particular, the findings highlight the potential role of movement amplitude as a (de)stabilizing factor in speech motor coordination.

Movement characteristics and coordination in the fluent and dysfluent speech production of an individual with apraxia of speech and Broca's aphasia

Apraxia of Speech (AOS) is typically described as a motor-speech disorder, demonstrating a limited ability to translate a presumably correct linguistic code into appropriate motor events (McNeil, Robin, & Schmidt, 1997; McNeil, Pratt, & Fosset, 2004). AOS is characterized by apparent disruptions in movement transitions within and between speech segments, leading to prolonged durations of individual speech sounds and of the transitions between sounds, syllables or words. These distortions are often perceived as sound substitutions and prosodic abnormalities (McNeil et al., 1997). Although the focus in the literature is on temporal characteristics (timing, sequencing), it has been argued that AOS also includes problems in spatial aspects of movement control, such as reaching specific spatial targets in the vocal tract for specific sound productions (Square, Roy, & Martin, 1997).

Most current theories regarding AOS propose that its core problem must reside at a stage of speech motor production during which an abstract linguistic code is transformed into a command that can be implemented by the speech motor execution system (e.g., McNeil et al., 1997; Aichert & Ziegler, 2004; and McNeil et al., 2004 for a review). There is little concrete information about this hypothetical stage, but it has been suggested that it utilizes a repository of abstract motor templates (Levelt & Wheeldon, 1994; Roelofs, 1997; Levelt, Roelofs, & Meyer, 1999). Based on this notion, some researchers claim that people with AOS have a problem in accessing this motor lexicon and are therefore forced to build motor "plans" from scratch each time they engage in speech production (Whiteside & Varley, 1998; Varley & Whiteside, 2001), which would correspond to the laborious and time consuming nature of their speech. This

theory has been criticized for various reasons (Ballard, Barlow, & Robin, 2001; Ziegler, 2001). Although there is some recent support for the existence of a syllable based motor lexicon (Cholin, Schiller, & Levelt, 2004, cf. Meyer, 1997), claims about ‘motor lexicon’ issues in AOS have found little support (Aichert et al., 2004).

Many accounts of the nature of motor problems in AOS focus on the planning of individual articulator movements. In a recent study, Clark and Robin (1998) suggested that a given individual with AOS might have limitations in either the abstract planning or the specific muscle command specification (but not both) of non-verbal oral motor tasks. Clark and Robin based the explanation of their findings on Schmidt’s Schema Theory (Schmidt, 1988), which draws a distinction between abstract generalized motor plans (i.e., not related to a specific effector system) and concrete motor programming (specifying force and temporal aspects of muscle activation) in limb control. A similar distinction has been proposed for speech production (e.g., Sternberg, Knoll, Monsell, & Wright, 1988; van Lieshout, 1995; Van der Merwe, 1997). In a recent review paper, McNeil (McNeil et al., 2004) endorsed this “planning and programming” model to explain the origin of speech motor problems in AOS. Although such an approach may provide some useful descriptors for differences in individual movement characteristics between speakers with AOS and controls, it is limited in its ability to address a very basic feature of AOS, namely the apparent problem in coordinating articulators with respect to a common task goal (e.g., McNeil et al., 1997; Square et al., 1997; Blumstein, 1998).

Unfortunately, experimental evidence for coordination problems in AOS is based on a limited number of studies, and among these only a few have looked at the behaviors of multiple articulators simultaneously (e.g., Itoh, Sasanuma, Hirose, Yoshioka, & Ushijima, 1980; Ziegler & von Cramon, 1986). The majority of studies in this area have focused on single articulator

data, for example, movements of the velum (Itoh, Sasanuma, & Ushijima, 1979), lower lip (McNeil, Caligiuri, & Rosenbek, 1989; McNeil & Adams, 1991), vocal folds (Hoole, Schröter-Morasch, & Ziegler, 1997), or tongue (Hardcastle, 1987; Katz, Bharadwaj, & Carstens, 1999). Other studies have analyzed acoustic events associated with the coordination of lip motion and phonation onset commonly referred to as voice onset time (e.g., Freeman, Sands, & Harris, 1978; Itoh et al., 1982; van der Merwe A., Uys, Loots, Grimbeek, & Jansen, 1989; Baum & Ryan, 1993). Overall, these findings suggest that coordination in people with AOS is more variable compared to normal speakers and that movement sequences are more segregated (i.e., showing reduced temporal cohesion). However, since most speakers with AOS also speak at a slower rate, it remains unclear if coordination is indeed a problem in itself, or if the observed variability and movement segregation is an epiphenomenon of the slower movement rate instead (see also McNeil et al., 1989; Adams, Weismer, & Kent, 1993).

To address this issue appropriately, one has to realize that coordination is more than just a simple summation of individual movements in time and space. This was emphasized and demonstrated many years ago by the Russian scientist Bernstein (1967), who argued that it is essential to create a functional dependency relationship (or synergy) between the individual components of a complex system (e.g., speech) that are involved in the execution of a specific task, in order to reduce the various control degrees of freedom (see also Turvey, 1990; Kelso, 1995). Coordination thus provides efficiency and compensatory flexibility to a complex control system, so that even when a single component structure is damaged, task goals can still be accomplished by compensatory coupling of the damaged structure to other structures that remain functional (see e.g., van Lieshout, Rutjens, & Spauwen, 2002). Therefore, in order to understand the nature of speech production problems in AOS, we need to gain a better understanding of the

potential limitations that exist in speech motor coordination, in addition to and beyond the presence of ‘abnormal’ individual movement characteristics.

To address this issue, we favour a theoretical perspective which focuses on coordination as a phenomenon on its own, instead of treating it as a derived characteristic of individual movements combined in time and space. This perspective is elegantly represented in the speech production models of Articulatory Phonology (Browman & Goldstein, 1992) and Task Dynamics (Saltzman & Kelso, 1987), which we will jointly refer to as “Articulatory Dynamics Theory” or ADT. For the reader who is less familiar with these models, we will briefly summarize the basic concepts of this model in relation to coordination at the different levels of speech production, because it has informed the way we have analyzed the kinematic data in this study.

In ADT the basic unit of speech production is the gesture, which is defined as a task-specific neural activation pattern in control of a flexible assembly of individual articulators to create a local constriction inside the vocal tract (Browman & Goldstein, 1990). Figure 1 shows a simplified diagram of the different levels of coordination defined in ADT, using time-aligned real movement data for the production of a bilabial stop to illustrate the degree of abstraction at each level.

[Insert figure 1 about here]

At the highest (i.e., most abstract) level we find the gestural representation, in this case a single task specification for bilabial closure. At this level, neural activation patterns govern the overall degree and location of vocal tract constrictions. The trajectory shown does not depict actual activation levels, but rather an abstract representation of the gestural involvement for this type of task, with a predominant closing component (downward trace). At the next level are the dimension-specific task implementations, which are referred to as tract variables in ADT

terminology. They are separate representations for lip aperture (vertical dimension) and protrusion (horizontal dimension) components. Finally, at the lowest (i.e., most direct observable) level, each tract variable specification is mapped onto a specific articulator, which requires a downward movement for the upper lip, and (distinctly different) upward movements for lower lip and mandible in this example for lip aperture. The nature of the coupling or coordination between the individual movements of the lips and jaw is constrained within the task specification of the original gesture. This low level type of coordination will be referred to as *intra-gestural* coordination (cf. Saltzman, Löfqvist, Kay, Kinsella-Shaw, & Rubin, 1998). The main influence on this type of coordination can be assumed to have a more peripheral (physiological/ biomechanical) origin (cf. Saltzman & Munhall, 1989; Fowler, 1995) as for example, induced by changes in movement rate and/or force.

The production of linguistic units such as words and/or syllables involves more than a single gesture. For example, even a simple VCV sequence like /api/ requires the coupling of two different gestures involved in tongue body constriction (tongue body + jaw) and bilabial closure in order to produce the proper acoustic events. This type of coordination is specified at the gestural level (top level box in figure 1) and will be referred to as *inter-gestural* coordination. Although physiological/biomechanical constraints may play a role through the influence of individual articulators (see below), it is at this level of coordination that linguistic (and other higher order) constraints are incorporated in the form of specific speech task requirements (Fowler, 1995). Such influences are traceable through for example, word stress and syllable structure manipulations (e.g., van Lieshout, Hiji, & Hulstijn, 1999).

Based on this approach, intra- and inter-gestural coordination measures tap into different levels of speech motor control. This is a highly relevant distinction for individuals with AOS,

because recent publications suggest that AOS involves differential deficits for tasks involving abstract versus more concrete (muscle specific) stages of motor preparation (Van der Merwe, 1997; McNeil et al., 2004).

Although ADT provides a very useful theoretical framework in which to explore different levels of coordination, it has been less explicit about some of the fundamental principles underlying the nature and stability of interaction between coupled articulators. These principles have received more attention in a related theoretical framework called Coordination Dynamics (Kelso, 1995; Kelso, 2000). Space does not permit a detailed account of this theory, but interested readers are referred to two recent papers in which the basic concepts of Coordination Dynamics are explained in the context of speech research (van Lieshout et al., 2002; van Lieshout, 2004). For this study, it is important to know that Coordination Dynamics theory proposes that specific intrinsic properties of the articulators exert a strong influence on the nature and stability of a task-specific coupling (Kelso, 1995). In particular, frequency and amplitude changes in the primary motions of articulators are claimed to (de)stabilize existing coordinative patterns (Buchanan, Kelso, deGuzman, & Ding, 1997; Fink, Foo, Jirsa, & Kelso, 2000; van Lieshout et al., 2002) when certain critical thresholds are exceeded. This type of nonlinear relationship between kinematic properties and coupling stability (coordination) is important to explore in the context of a speech disorder like AOS in order to understand potential sources of interruptions in the fluency of speech production (see also Bose, van Lieshout, & Square, 2003 for a similar approach with aphasic subjects). It is also important to investigate whether different levels of coordination (intra- and inter-gestural) are equally influenced by such kinematic properties. One would expect that lower levels of coordination might be more susceptible to

dynamics properties of individual movements, but as recently shown, low level dynamics do influence higher order (inter-gestural) coordination patterns (Saltzman et al., 1998).

The Present Study

In the present study, we recorded the movements of upper lip, lower lip, tongue tip, tongue body and jaw for a young adult female speaker with AOS and Broca's aphasia. This subject was a fairly unique case, as she was at an age (30 years) where cerebrovascular accidents are infrequent (Nightingale & Farmer, 2004; Petitti, Sidney, Quesenberry, & Bernstein, 1997). Her clinical profile has been defined in great detail in a different manuscript documenting the effects of a specific speech motor therapy (Bose, Square, Schlosser, & van Lieshout, 2001). Given her relatively young age, we were able to study speech motor behaviors unaffected by the age related changes that are inevitably part of the speech presentation of older populations of patients with AOS, such as those used in the majority of (speech) movement studies in this area (e.g., see Sosnoff, Vaillancourt, & Newell, 2004 for the effects of aging on the adaptability to coordinate multiple neural oscillators in rhythmical force production). As appropriate reference data for this age category are lacking for the type of measures used in this study, it was deemed necessary to compare our subject's fluent speech motor characteristics to a group of age matched male and female control speakers to incorporate gender-specific variations in speech motor parameters (Simpson, 2001). In performing these tests, the main purpose is to establish whether these movement variables can differentiate fluent speech samples of our subject with AOS and Broca's aphasia from similar data collected from normal speakers and thus provide a potential window on basic speech motor control issues in this population. Similar strategies have been used in other populations with speech problems, for example in people who stutter (van Lieshout, Hulstijn, & Peters, 1996).

In the second part of our analysis, we compared specific kinematic and coordination measures acquired during fluent speech production of our subject with the same measures gathered from samples containing dysfluent speech. This allowed us to speculate about underlying speech motor control mechanisms, especially with regard to the presence of compensatory strategies in the control of fluent speech (van Lieshout, Hulstijn, & Peters, 2004). To our knowledge, such an explicit and detailed comparison has not been performed thus far and may shed some light on the sometimes conflicting results on kinematic characteristics of AOS as presented in the literature. In addition, as set out in the previous sections, it can be used to evaluate some of the earlier claims on the appropriateness of using the ADT model for studying speech motor behaviors in AOS (Kelso & Tuller, 1981), in particular with respect to a potential disruption of the coupling between articulators and/or gestures as the basic source of error in this population (see also Ziegler et al., 1986).

Methods

Subjects

The experimental subject was a 30-year-old right-handed female, highly educated and a native speaker of Canadian English (AS). She suffered a left-hemisphere cerebrovascular accident (CVA) secondary to hemorrhage from the rupture of a congenital arteriovenous malformation. A large lesion occupying the left frontoparietal occipital region was evident on CT scans one month after the incident. At that time, she was characterized as having severe non-fluent Broca's aphasia with pronounced oral and verbal apraxia and a right hemiparesis.

At the time of this study, she was 13 months post-onset. A summary of a detailed speech and language assessment, which included both standardized and non-standardized measures, appears in table 1 (for more details see Bose et al., 2001).

[Insert table 1 about here]

Spontaneous language samples were characterized by short phrases and grammatically simple constructions marked by agrammatic errors. In general, speech was slow and labored, showing initiation difficulties, articulatory groping, visible and audible searching, self-rehearsals, phonemic errors and distortions, difficulty in sequencing movements with increased utterance length, and varied off-target attempts at words. Naming tasks revealed word-finding difficulties, including circumlocutory responses, and both semantic and phonemic paraphasias. Repetition was impaired for phrases greater than seven syllables in length. AS exhibited less difficulty producing automatic versus volitional speech. Apart from her mild right facial hemiparesis, a detailed motor speech examination revealed no significant abnormalities in muscle tone or strength, and no classifiable dysarthria as defined by Duffy (Duffy, 1995). Prior to participating in this study, she had completed a year of in-patient and outpatient rehabilitation, which included general speech and language treatment, physical and occupational therapy. However, she did not receive any specific speech motor based interventions. Based on her clinical profile our subject fits the necessary and sufficient criteria for the differential diagnosis of AOS as proposed by McNeil et al. (2004).

The reference group of normal speaking subjects (NS) consisted of 6 young adults (4 females and 2 males) of comparable age to our subject with AOS (mean age = 27.7 years, SD = 4.3 years, range = 23-35 years) and with comparable educational experience. They all used English as their first language and had no reported history of speech, language, or hearing problems.

Experimental Tasks

All subjects repeated one of three different non-word¹ tasks ([api], [ipa], & [patəka]) in a single trial for about 12 seconds in a preferred rate. We refrained from imposing a specific speech rate on our subjects, given potential limitations in controlling speech at different rates for patients with AOS² (Ziegler, 2002) and also because we wanted to assess speech motor control under normal rate circumstances, as fast and/or slow rates show atypical signal characteristics (Westbury & Dembowski, 1993; van Lieshout & Moussa, 2000) and potentially also differ in terms of neural control (Wildgruber, Ackermann, & Grodd, 2001).

The bi- and tri-syllabic stimuli were selected in order to allow the study of both intra (between single articulator movements) and inter (between consonant and vowel gestures) gestural levels of coordination within a single task. We used these non-words to focus our attention on processes at or below the level of phonology, as this is where speech problems for people with AOS are believed to have their origin (see introduction). These specific tasks have been shown to differ in ease of articulation (van Lieshout et al., 2000; van Lieshout, Hulstijn, Alfonso, & Peters, 1997). Our approach follows a common practice of using non-words either embedded in a stereotypical short sentence frame or simply being reiterated to detect limitations in speech motor control (e.g., Ackermann, Hertrich, & Hehr, 1995), even though certain problem areas in AOS may be underestimated when compared to more natural speech production (Ziegler, 2002).

The three tasks will be referred to as API, IPA and PTK. Each task involved a bilabial closure gesture for a voiceless stop [p] and tongue body constriction gestures for vowel

¹ The term non-word is defined here as a pronounceable meaningless string of letters with a well-defined syllabic structure.

² Our original instruction to the subject with AOS was to change rate while reiterating the stimuli, but she was not able to do so and we allowed her to repeat all tasks at her own preferred rate.

alternations. We will refer to each reiterated speech task as a trial-set. Trial-sets for the three tasks used in this study were embedded in a larger block of trial-sets with other stimuli (not reported here). For all speakers, the target trial-sets were extracted from 2 sessions conducted on different days to allow for normal day-to-day variation in kinematic parameters (Alfonso & van Lieshout, 1997). For AS who participated in a speech motor therapy as part of a different study mentioned above (Bose et al., 2001), only baseline data were used to avoid any potential therapy based influences.

Instrumentation

All data were collected using time-aligned audio and Electro-Magnetic Midsagittal Articulography (EMMA) position signals from the AG100 system (Carstens Medizinelektronik, GmbH, Germany) with a large helmet size (62 cm diameter) and automated calibration. All position data were sampled at 400 Hz, while acoustic data were acquired at 16 kHz. Further details about this equipment are described elsewhere (van Lieshout et al., 2000).

Procedures

Transducer coils were attached to the midline positions of the vermilion border of upper and lower lip, the posterior surface of a thin thermo-plastic custom made mould covering the lower incisors, the tongue blade (1 cm behind tongue tip), the tongue body (3 cm behind tongue blade coil), and tongue back (approximately 2 cm behind tongue body coil). Two additional coils were attached to the gums of the upper incisors and the bridge of the nose to detect (and correct for) head movements. All coils were attached with surgical methacrylate resin (Cyanodent, Ellman International Mfg.).

Following coil attachment, we measured the occlusal bite plane, using a plastic device with two coils attached in the midline at a fixed distance of 3 centimeter. Subjects held the

device in their mouth using their teeth for about 3 seconds. The upper incisors touched the device just behind the posterior transducer coil (cf. Löfqvist, 1991; van Lieshout et al., 2000). For speech data collection, a computer monitor was positioned at a distance of 1.5 meters in front of the chair in which subjects were seated. An acoustic and visual warning signal indicated the upcoming presentation of a stimulus on the screen. Each stimulus was presented on the center of the screen in a large font for about 4 seconds. During this preparation interval, the subject also received a warning to take a deep breath to allow him/her to repeat the stimulus for 12 seconds in a single breath (if possible). After the preparation interval, another acoustic and visual signal indicated to the subject to begin repeating the stimulus according to the specified rate instructions (see above). The stimulus remained in sight throughout as a reminder. After 12 seconds the stimulus would disappear from the screen and an acoustic signal indicated the end of a trial-set. Subsequent trial-sets were initiated when the subject indicated that he/she was ready.

Data processing

Movement data were smoothed using an 11-point triangular filter (effective low pass frequency 27.5 Hz) prior to processing. Subject-specific occlusal plane data were rotated to align them with the EMMA horizontal axis. Thus, a uniform coordinate reference frame was established for all subjects (Westbury, 1994). For the individual articulator data, movement signals were band-pass filtered with a 7th-order Hamming windowed Butterworth filter using 6.0 Hz and 0.1 Hz as the high and low cut-off points. This procedure removes DC drift and higher-frequency noise components but preserves the main motion components (van Lieshout et al., 2000). For the kinematic measurements, lower lip signals were corrected for jaw movements using an estimate of jaw rotation based on the principal component of the mandible coil trajectory (Westbury, Lindstrom, & McClean, 2002). Compared to a simple subtraction method,

which ignores jaw rotation, this method reduces positional and speed errors by approximately 65-70% (Westbury, 1988; Westbury, Lindstrom, & McClean, 2002).

To study inter-gestural coordination, we calculated a gestural measure of bilabial closure (BC) as the two-dimensional Euclidean distance between the upper lip and the lower lip plus mandible. Similarly, the gestural position of the tongue tip/blade (TT) and tongue body (TB) coils was calculated as the two-dimensional Euclidean distance from the nasal reference coil. By convention, gestural measures will be labeled using uppercase letters. Similar procedures for incorporating both vertical and horizontal displacement to reflect the abstract task dependent nature of gestures (see figure 1) have been reported previously in the speech literature (Saltzman, Byrd, Saltzman, & Byrd, 2000; Byrd & Saltzman, 1998). Figure 2 shows an example of a PTK trial-set for a control subject, with position information for the three gestures TB, TT, and BC, as well as for the vertical (up/down) dimension of the upper lip (uly), lower lip (lly), and jaw (jwy) motion (see below for more information on these variables). Notice that for the gestural data, downward displacement of the waveform indicates a smaller combined XY distance relative to the nose coil (i.e., effectively a movement towards the palate or a high degree of constriction). The rectangular shape defines the virtual boundaries (between successive bilabial closures) for a single PTK utterance. The upper two panels show the spectrogram and acoustic waveform respectively. For orientation purposes only, the approximate “target” positions for [p], [t], and [k] are labeled.

[Insert figure 2 about here]

Dependent variables

Following the data processing procedures described above, kinematic parameters were derived from the movement data. Details about these procedures can be found elsewhere (van

Lieshout et al., 2002; van Lieshout et al., 2000). For this study, we focused on three traditional kinematic measures, namely movement duration (DUR in ms), peak velocity (PV in mm/s) and amplitude (AMP in mm; i.e., movement range from valley to peak and vice versa) and three derived parameters: kinematic stiffness (STIF = peak velocity/amplitude in 1/s), velocity profile parameter (VPP in a.u., in the literature also referred to as constant C = stiffness * duration, e.g., Munhall, Ostry, & Parush, 1985), and velocity profile symmetry index (VPS in %, in the literature also referred to as % time to peak velocity, e.g., Adams et al., 1993). These parameters are based on a frictionless mass-spring model of single axis motions (e.g., Perkell, Zandipour, Matthies, & Lane, 2002). According to this model, stiffness acts as the control parameter for frequency of oscillation (or resistance to change in motion) and it has been suggested that it can be an important parameter for describing motor control differences in populations with speech disorders (e.g., Ackermann, Hertrich, & SCHARF, 1995). VPP is an index for the shape of the velocity profile (e.g., 1.7 indicates a single-peaked shaped profile), and VPS is an index of the relative time spent on acceleration during opening and closing movements (with a value of 50% indicating a perfectly symmetrical velocity profile with equal time allotted to acceleration and deceleration). These mass-spring model based measures have been discussed at length in the literature on normal speakers (e.g., see Adams et al., 1993; van Lieshout et al., 2000; Perkell et al., 2002; Munhall et al., 1985; Shaiman, Adams, & Kimelman, 1997) and to some extent, they have also been used in studies for speakers with AOS (e.g., McNeil et al., 1991). Specific changes in these parameters are assumed to reflect differences in motor control strategies (see also Perkell et al., 2002 for a discussion of this topic), that is, these parameters may be sensitive to motor control differences between normal speakers and AOS that are not detectable in the more traditional measures of movement amplitude, peak velocity and duration (see also

Ackermann et al., 1995). Earlier studies (e.g., Forrest, Adams, McNeil, & Southwood, 1991) have shown for lower lip that differences between normal speakers and speakers with AOS were most prominent for closing movements. Thus, we restricted our analysis of individual articulators to closing movements, which were labeled as follows: upper lip (uly), lower lip (lly), tongue body³ (tby), and jaw (jwy).

In a recent review, McNeil suggested that higher coefficients of variation (CV) values for peak velocity might be a distinctive feature of AOS (McNeil et al., 2004). CV's indicate how consistently a speaker is able to achieve the same values for a given movement target during the repetition of a task. To test this assumption for our subject, we included CV's for the peak velocities of the articulators of interest mentioned above.

In addition to these individual kinematic parameters, we also calculated a cyclic spatio-temporal index (cSTI) (van Lieshout et al., 2002) based on the STI measure described by Smith and colleagues (Smith & Goffman, 1998; Smith, Goffman, Zelaznik, Ying, & McGillem, 1995). CSTI values reflect pattern variability across individual movement cycles and thus can be used to identify (short-term) changes in the stability of speech motor execution. In order to calculate cSTI, individual orientation-specific movement cycles, defined by the peaks and valleys in the signal, are amplitude- and time-normalized and aligned with each other. Separate standard deviations for the overlapping segments are then computed at 2% intervals in relative time. CSTI is defined as the sum of these standard deviations within a plane of movement (vertical or horizontal). Figure 3 shows an example of a cSTI analysis for the same upper lip and lower lip data depicted in figure 2 (PTK task) with the original and filtered signals (as used for the analysis), and the segmented individual cycles (raw, amplitude & time normalized). As shown, both lip movements were highly stable (= consistent) in this example.

³ Tongue blade movements were only used to obtain information on inter-gestural coordination in the PTK task.

[Insert figure 3 about here]

To measure coordination between individual articulators and between gestures, we employed a new approach compared to that used in previous studies (e.g., van Lieshout et al., 2002). First, we applied a cross-spectral coherence analysis (e.g., Aoyagi, Ohashi, Tomono, & Yamamoto, 2000; Boose, Spieker, Jentgens, & Dichgans, 1996; Kay, 1988). With this technique we can measure the correlation between individual spectral bins of Fourier transformed position signals with a resolution of 0.1 Hz (van Lieshout, 2001). A high correlation ratio for a given spectral component indicates a strong entrainment between the two signals at that particular frequency. Figure 4 shows an example of a cross-spectral analysis for TB and BC signals for the same trial-set as depicted in figure 2 (PTK task). The graph shows strong and highly correlated peaks at 2.8 Hz in both signals. We refer to these spectral components as motion primitives (van Lieshout, 2001) in line with recent models of motor control where movement signals are treated as combined influences of neural pattern generators (Bizzi & Mussa-Ivaldi, 1998; Woch & Plamondon, 2004). The dominant motion primitive for each trial-set (at the frequency showing the highest power and/or the highest spectral correlation across the two signals) was selected as the input for the subsequent relative phase analysis, because it provides a clean estimate of the main control influence on the motion pattern across time.

[Insert figure 4 about here]

Relative phase provides a time and amplitude normalized index of relative timing between two articulators or two gestures (Kelso, Saltzman, & Tuller, 1986; van Lieshout et al., 2002). To this end, point-differentiation was used to obtain velocity versus time functions from the position signals. The position and velocity signals were then band-pass filtered using the dominant peak (identified in the cross-spectral analysis procedure described above) as the center

frequency (± 0.2 Hz). These signals were processed in a standard way (e.g., van Lieshout et al., 2002) to obtain continuous estimates of relative phase. For intra-gestural coordination we calculated relative phase signals for upper lip and lower lip motions, whereas for inter-gestural coordination we calculated relative phase signals for BC vs. TB in API and IPA tasks. For PTK, we made two comparisons in order to differentiate between phase coupling for tongue and lip movements related to bilabial and alveolar sound productions (/p/ vs. /t/: TT vs. BC) and for tongue movements related to alveolar and velar sound productions (/t/ vs. /k/: TB vs. TT). All relative phase variables are expressed in degrees.

To measure the stability of coordination, we used the within-trial-set (circular) standard deviation of relative phase (van Lieshout et al., 2002; van Lieshout, 2004; Kelso, 1995). Figure 5 displays an example of a relative phase signal for the same tongue body constriction (TB) and bilabial closure (BC) gestures shown in figure 4 at 2.8 Hz. In this example, the coupling is very stable (SD = 6.03 deg) at 271 deg, a typical value found for this type of task (van Lieshout, 2001).

[Insert figure 5 about here]

For the present study, the following dominant motion primitive values were derived for intra- and intergestural coordination calculations. For AS the average (across trials) and standard deviation (SD) values for the dominant motion primitives were 1.8 (0.25) Hz, 1.7 (0.19) Hz and 2.3 (0.36) Hz for API, IPA and PTK respectively. For our group of control speakers the average (across trials and subjects) and SD values for API, IPA and PTK were 1.9 (0.39) Hz, 2.0 (0.41) Hz, and 2.0 (0.59) Hz. Differences are small, but do notice that whereas controls show virtual no task related changes, AS had higher values for PTK compared to API and IPA. All values are well within normal limits for rate variations in speech production.

Speech sample selection

All trial-sets from our subject with AOS were screened for errors in performance and/or the presence of disfluencies. Only portions that were spoken in a perceptually correct and fluent way, and for which the kinematic data revealed no obvious errors or deviations (e.g., interruptions of ongoing movements) were selected for the first part of the results section of this study. For the control speakers we also selected only error-free speech samples. In this we followed procedures developed over the years for extracting fluent speech samples from physiological data in people who stutter (e.g., van Lieshout et al., 1996).

For the second part of the results section of this study, we only used data from AS. We coded samples of her kinematic data as either error free (i.e., as defined for part 1) or containing errors of several different types: initiation difficulties, articulatory groping, visible and audible searching, self-rehearsals, phonemic errors and distortions, difficulty in sequencing movements, and off-target attempts at tasks. Errors related to technical difficulties or pauses related to inhalation before the end of a trial-set was reached were not included in these samples. Given the inherent difficulty in making accurate decisions on the exact nature of these speech problems, and the fact that there would not be sufficient occurrences of each of these categories, we did not further attempt to classify the errors. Instead, we simply labeled stretches of speech containing such errors as dysfluent speech. In addition, we separately coded the 1-second intervals preceding the onset of each dysfluent speech interval to determine if specific kinematic changes occurred prior to the onset of overt dysfluent speech behaviors. This could provide useful preliminary information regarding mechanisms that potentially give rise to interruptions of fluent speech (van Lieshout et al., 2004). Figure 6 shows a typical example of a coded trial-set, with ‘1’ indicating intervals of normal fluent speech, ‘2’ indicating 1-second intervals immediately

preceding sections of dysfluent speech, and '3' indicating intervals of overt dysfluent speech.

[Insert figure 6 about here]

Statistical analysis

For part 1 of the analysis, the data that are shown for each dependent variable are averaged across the extracted error-free speech samples for each task separately. Comparing a single individual to a group of subjects has its challenges, but it is a fairly common procedure in cognitive neuropsychology case studies. From this literature, recent papers discussed and promoted the use of a statistical approach as opposed to a less rigorous comparison with only descriptive statistics (Mitchell, Mycroft, & Kay, 2004; Crawford, Garthwaite, Howell, & Gray, 2004; Mycroft, Mitchell, & Kay, 2002). We applied the F-test (repeated measures ANOVA) proposed by Mycroft and colleagues (Mycroft et al., 2002). In order to correct for possible differences in the population variance between normal speakers and patients with AOS, it is required to adjust the F-criteria for these tests. There are no reliable kinematic reference data to estimate such a potential difference, but for comparing fluent speech samples we adopted a cautious 1.5:1 ratio, which at the 0.05 level would require us to accept a difference as significant when the F-ratio is 10 or higher. This is a rather conservative approach (Crawford et al., 2004), which is why we did not use further (Bonferroni) corrections to account for the fact that we are testing multiple dependent variables. With these modified F-criteria, a significant finding would indicate a true difference in the mean score of AS when compared to the scores of NS. Differences which were not found to be significant under the stringent criteria applied here, but showed a trend as defined by a more relaxed p-value ($< .1$), with an uncorrected F-value at $df(1,5) = 4.06$ as a lower limit, will be highlighted as well. As mentioned in the introduction, in performing these tests, the main purpose was to establish whether and how these movement

variables differentiated fluent speech samples of AS from normal speakers and would warrant further scrutiny in future studies. To this end, we also needed to demonstrate that our tasks did challenge AS in terms of producing fluent speech. A useable estimate for this is the average length of time of fluent speech per trial set for each task; smaller values basically mean more speech errors for a given task. In our analysis, we used AS versus NS as our “GROUP” factor (between-subjects) and TASK (API, IPA, & PTK) as our within-subject factor. Separate analyses were performed for individual articulator closing movement parameters (upper lip, lower lip, tongue body, & jaw) and coordination data (intra- and inter-gestural). Main effects for TASK were further explored using Tukey-Kramer post-hoc tests to identify individual task differences.

For part 2 of the analysis, we averaged the data within the coded sections (CODE) for each task. For this analysis, we selected movement range (AVAMP), peak velocity (AVPV) and duration (AVDUR) for the bilabial closure (BC) and tongue body constriction (TB) gestures in API and IPA and for tongue body constriction (TB) and tongue tip/blade (TT) constriction gestures for PTK. This focus was mostly for practical reasons, but it is also at this higher level of motor coordination that the current literature suggests AOS might be expected to express itself most clearly (e.g., McNeil et al., 2004). In addition to these individual gesture data, inter-gestural relative phase mean and within-trial-set variability values (for the dominant motion primitive) were included in this analysis. We performed a within-subject ANOVA with GESTURE (TB and BC in API/IPA, and TT and TB in PTK) and CODE (intervals #1, #2 or #3) as independent variables for the kinematic data, and an analysis on TASK (API, IPA, & PTK) and CODE for inter-gestural coordination (TB with BC for API & IPA, TB with TT for PTK), with the alpha level set at $p < .05$. Tukey-Kramer post-hoc tests were used where appropriate. All statistical tests were performed with Number Cruncher Statistical Software (NCSS) 2000 (Hintze, 1998).

Results

Before presenting the kinematic and coordination data, we will report the test results for the average duration (in seconds) of the error free speech intervals per trial set for each task. The data are shown in figure 7. Overall, AS had shorter stretches of fluent speech (within a trial set) compared to NS, but the difference is especially clear for the IPA and PTK tasks. NS showed virtually no difference across tasks. Although the main GROUP difference failed to reach significance [$F(1,7) = 3.72$, $p = 0.95$], but the main trends for TASK [$F(2,14) = 8.43$, $p = .004$] and the GROUP x TASK interaction [$F(2,14) = 5.85$, $p = 0.014$] confirmed the task specific reduction in fluent speech for AS. Thus, our tasks, in particular IPA and PTK were challenging to AS. This was also our impression while listening to her speech during the experiment. The difference between API and IPA confirms the findings from earlier studies on normal speakers, where it was found that IPA proved to be more difficult to articulate at higher speeds than API (van Lieshout et al., 2000; van Lieshout et al., 1997).

[Insert figure 7 about here]

Part 1

Table 2 presents the means and standard deviations (SD) for all kinematic data, shown separately by task and articulator. The repeated measures ANOVA test results are summarized in table 3. From these tests results it is clear that none of the kinematic variables indicated a significant difference between fluent speech samples from AS and NS. In fact, based on the distributional characteristics of the NS data, we estimated that in order to find a significant difference⁴, AS should have shown means that would be minimally 2.2 times the SD of the control speakers (across tasks). We calculated the appropriate lower and upper limits of this distribution, rescaled it to a 100% range and plotted AS' values (across tasks) in this range to indicate how her data

fitted this distribution. To clarify, statistical significance would only be obtained for values falling above or below this range (figure 8).

[Insert tables 2 & 3 and figure 8 about here]

Clearly, most variables fell in the 30-70% midrange, and only three upper lip variables (AMP, PV, and VPP) reached a position above the 70% mark of the distribution. For uly AMP and PV, this is confirmed by a trend towards a GROUP difference (table 3).

Some variables showed a significant effect or trend for a GROUP x TASK interaction (table 3). Significant interaction effects were obtained for tby duration and tby VPP contrasts (figure 9). Both variables show similar patterns for AS; higher values for API and IPA, lower values for PTK compared to NS. In fact, for duration, NS showed hardly any task differences whereas for VPP, their data showed an almost linear increase from API to PTK. Trends were found for jwy AMP, uly PV, lly PV, jwy PV, uly DUR, and tby cSTI (see tables 2 + 3). The trend for jwy AMP and PV indicated that AS showed clearly higher values for API, smaller differences for IPA and no difference for PTK when compared to NS. For uly PV, PTK showed a much stronger increase in peak velocity for AS when compared to NS. For uly duration, the difference was similar to what was found for tby duration, viz. NS showed no task difference, but AS showed a marked decrease in duration for PTK (in fact, this was seen for all duration measures). Finally, tby cSTI echoed the change in duration, with small differences between API and IPA and a sharper increase in cSTI for PTK when comparing AS with NS.

[Insert figure 9 about here]

Main TASK effects were prominent for amplitude and peak velocity variables in all articulators. Upper lip showed the opposite pattern of the other articulators, with smaller values for API and IPA compared to PTK (see table 2). For other variables, task effects were limited to

⁴ Based on one-tailed t-test appropriate for this type of comparison Crawford et al., 2004.

a specific articulator (tby and jwy duration; lly and jwy stiffness; jwy VPS; jwy cSTI; jwy CV-PV) or completely absent (VPP). The shorter movement duration for PTK was mirrored in higher stiffness and variability values in these articulators.

Regarding intra- and inter-gestural coordination (see table 4), as with the kinematic data, none of the GROUP differences reached significance. However, for intra-gestural coordination we did find a trend for lower values across the three tasks in AS [$F(1,7) = 5.42, p = 0.053$]. There was also a significant TASK effect [$F(2,14) = 22.33, p < .001$] and a trend for an interaction [$F(2,14) = 4.08, p = 0.04$]. The TASK effect showed a significantly higher value for IPA compared to API and PTK. Basically, this means that for IPA the lower lip leads on average (> 180 deg), whereas for the other two tasks, the upper lip leads (< 180 deg). The interaction trend reflects the greater AS vs. NS difference in relative phase for lip coordination in PTK compared to the other two tasks.

A significant TASK effect was also found for inter-gestural coordination [$F(3,21) = 297.13, p < .001$], but no effect or trend of GROUP [$F(1,7) = 2.1, p = .191$] or GROUP x TASK interaction [$F(3,21) = 1.75, p = 0.188$]. The TASK effect for inter-gestural coordination reflected systematic differences between values in three distinct phase regions which were roughly bounded by the 90 deg, 180 deg, and 270 deg marks. Coordination data are shown in figure 10.

[Insert table 4 and figure 10 about here]

With respect to relative phase variability (see table 4), there were no effects or trends for GROUP [intra: $F(1,7) = 0.19, p = 0.672$; inter: $F(1,7) = 0.02, p = 0.886$], TASK [intra: $F(2,14) = 0.7, p = 0.511$; inter: $F(3,21) = 3.2, p = 0.044$] or interaction [intra: $F(2,14) = 1.29, p = 0.305$; inter: $F(3,21) = 2.26, p = 0.111$]. In other words, both intra- and inter-gestural coupling was stable for all three tasks in the fluent speech of AS and NS alike.

Part 2

Using the coding system explained in the methods section (CODE: 1 = intervals of normal fluent speech, 2 = 1-second intervals immediately preceding sections of dysfluent speech, and 3 = intervals of overt dysfluent speech; see figure 6), we calculated the average values for amplitude (AVAMP), peak velocity (AVPV) and duration (AVDUR) estimates of gestural movements (GESTURE = BC, TB, or TT; i.e., changes in these parameters relate to Euclidian distance estimates) and their coupling (relative phase and within-trial-set standard deviation of relative phase). The kinematic data are shown in figure 11. Following is a description of the ANOVA test results.

[Insert figure 11 about here]

For *AVAMP*, we found a significant effect for CODE [$F(2,99) = 4.06, p = .02$]. There was a significant GESTURE effect [$F(2,99) = 17.93, p < .001$], but no CODE X GESTURE interaction [$F(4,99) = 0.86, p = 0.491$]. Amplitudes showed a clear reduction during dysfluent speech production, compared to fluent speech, except for TT. This reduction in amplitude is already visible before the actual onset of disfluencies (as shown for #2 samples).

For *AVPV*, we again found a significant effect for CODE [$F(2,99) = 6.59, p = .002$] and a main effect for GESTURE [$F(2,99) = 16.57, p < .001$]. The interaction did not reach the required levels for significance or trend [$F(4,99) = 0.98, p = .422$]. As shown in figure 11, similar to amplitude, there was a clear downsizing of peak velocities from error-free speech to dysfluent samples for TB and BC, with #2 samples in between. Unlike amplitude values, even TT showed a similar trend. Overall, as with amplitude, PV values for TT were smaller compared to BC and TB.

For *AVDUR*, we found significant main effects for CODE [$F(2,99) = 3.16, p = .046$] and GESTURE [$F(2,99) = 7.17, p = .001$], but no interaction [$F(4,99) = 0.09, p = .986$]. Post-hoc tests revealed a significant difference between the #2 samples (smaller values) compared to the dysfluent samples (#3). In terms of average duration, as with the other variables, TT data showed smaller values compared to the other gestures (figure 11).

[Insert figure 12 about here]

Gestural coordination data are shown in figure 12. In terms of relative phase or *PHI*, we did not find a main effect or trend for CODE [$F(2,43) = 1.17, p = .31$]. We did find a significant TASK effect [$F(2,43) = 256.80, p < .001$] and a significant CODE x TASK interaction [$F(4,43) = 2.90, p = .033$]. As shown in figure 12, phase values are quite stable across the different speech samples for each task, but dysfluent speech does induce some changes to inter-gestural coupling, be it in different ways for API (higher values) compared to IPA and PTK (lower values). Overall, phase values remained within or close to their original boundaries as discussed in part 1. This means that the basic nature of the coupling (i.e., its specific phase lag) was not strongly influenced by the fact that speech was dysfluent.

For the within-trial-set standard deviation of relative phase or *SDPHI*, we found a significant CODE effect [$F(2,43) = 4.57, p = .016$]. There was no main effect for TASK [$F(2,43) = 0.01, p = .985$], nor an interaction with CODE [$F(4,43) = 0.48, p = .153$]. Post-hoc tests showed higher values for #3 samples compared to #1 and #2 (fluent speech) samples (figure 12). In other words, dysfluent speech was characterized by higher variability in gestural coordination.

Discussion

The first part of this study was set up to establish whether movement variables could differentiate fluent speech samples of a young female speaker with AOS and Broca's aphasia

from similar data collected from normal speakers and would warrant further scrutiny in future studies. In the second part of our analysis, we compared specific kinematic and coordination measures acquired during fluent speech production with the same measures gathered from samples containing dysfluent speech. This allowed us to speculate about underlying speech motor control mechanisms in our subject, especially with regard to the presence of compensatory strategies in the control of fluent speech (van Lieshout et al., 2004). We performed a detailed analysis of individual movement characteristics (closing movements) and two levels of coordination (intra- and inter-gestural) in movement data from upper lip, lower lip, tongue body, tongue tip/blade, and mandible, acquired during reiterated non-word utterances (API, IPA, & PTK). These tasks were found to be sufficiently challenging to our subject (especially IPA & PTK) to generate a fair amount of dysfluent speech samples.

The findings of Part I revealed that in applying strict statistical criteria for comparing an individual's performance to a group of controls (Mycroft et al., 2002), kinematic characteristics for AS were well within normal limits during fluent speech production. Only for upper lip amplitude and peak velocity, we found a general trend for higher values for AS compared to NS. However, it was also quite apparent that the three tasks showed different profiles for most kinematic variables. In general, the PTK task was very different from the two bisyllabic tasks API and IPA, showing smaller, faster and more variable closing movements. These task related differences played a role in comparing AS with NS, as indicated by several statistically notable (significant or trend) interactions.

First, our subject AS in general executed error-free speech movements with larger amplitudes, peak velocities and durations while reiterating bisyllabic tasks (especially API), but this was not true for PTK, except for upper lip amplitude and peak velocity. When task-related

changes occurred in higher-order derived kinematic variables (stiffness, VPP and VPS), these were consistent with the main differences seen in amplitude and/or duration. It should also be noticed that in fluent speech AS did not show a consistent pattern of higher variability in cyclic movement patterns. VPS and CV-PV were the only variables that revealed no (general or task-related) differences between AS and NS during fluent speech. Obviously, this does not mean that they cannot change during dysfluent speech, which may account for group differences found for these variables in other studies (Adams et al., 1993; McNeil et al., 2004).

In terms of coordination, AS showed a trend towards overall lower values for intra-gestural coordination but not for inter-gestural coordination. Despite this difference in the type of coupling, the variability of both coordination measures was not significantly different compared to controls during the production of fluent speech. For lip coordination, API and PTK induced an overall dominant upper lip lead, whereas for IPA lower lip lead was the preferred pattern. For inter-gestural coordination, we found three clearly distinct regions of phase coupling for the four gestural configurations across all subjects (TB-BC in API & IPA; TT-BC and TT-TB for PTK) with no inherent differences in stability. The latter finding supports claims from ADT on the specific nature and relative stability of couplings in gestural phasing (Saltzman et al., 2000).

Part 2, which involved a direct comparison between error-free and dysfluent speech samples produced by AS, showed a significant downsizing of amplitude and peak velocity values for speech immediately preceding and during the production of dysfluent speech. These changes in kinematics were associated with changes in the stability of inter-gestural coupling (lower for dysfluent speech), but not in the nature of the coupling.

Comparing the kinematic findings of the present study with data reported in the literature on people with AOS (with or without aphasia), the longer duration found for bisyllabic tasks is in

agreement with (the few) other kinematic studies for this population (see McNeil et al., 1997, for a review). These increased movement durations can (to some extent) be assumed to underlie the longer durations within and between segments reported in acoustic and perceptual studies, as discussed in the introduction to this paper. Interestingly, the longer durations were not found for PTK, which calls into question the general nature of this phenomenon. More about this further down.

With respect to larger movement amplitudes and peak velocities found for bisyllabic tasks, the correspondence with previous literature is less clear. One study reported larger amplitudes but normal peak velocities for subjects with AOS (McNeil et al., 1989). Another study reported lower peak velocities (Itoh et al., 1980), but most studies have not found evidence of systematic differences in amplitude and/or peak velocity (Itoh & Sasanuma, 1987; McNeil et al., 1991; Robin, Bean, & Folkins, 1989). In part, these discrepancies may be attributable to differences in the procedures used to select data (error-free vs. dysfluent speech samples or a mixture of both), or to differences between individual subjects and their clinical profile (see McNeil et al., 2004 for an extensive discussion of the latter topic). Our subject was also younger than the subjects used in previous kinematic studies, which may add to the observed differences. Also, it is important to keep in mind that discrete kinematic parameters may show variation within a subject across time (Alfonso et al., 1997), a reason why we (unlike other studies) collected data over two different sessions, spread in time.

However, the interpretation of kinematic findings is not a simple matter and needs to be discussed in a broader perspective. One way to do this is to take a theoretical approach, based on assumptions derived from the mass-spring model (e.g., see Munhall et al., 1985; Ostry & Munhall, 1985; Perkell et al., 2002). If we explore this model a bit further, we can make specific

predictions about the nature of changes in the different variables as a function of motor demands. This is shown in figure 13.

[Insert figure 13 about here]

The graph depicts amplitude, peak velocity and durational changes within the constraints of a single-peak velocity profile, typically found in (quasi) sinusoidal movement patterns (an example of which is shown in the upper right-hand corner of the graph). Different configurations pertaining to changes in individual kinematic parameters are numbered 1 to 4. The legend below the graph indicates the expected changes in the dependent variables if a subject changed either amplitude (e.g., 1 vs. 2), or duration (1 vs. 3), or both (1 vs. 4) as part of the speech task requirements. Since all tasks have to be executed under single-peak velocity constraints, VPP and VPS values remain the same (1.57 and 50% respectively). If a subject simply makes smaller movements for one task compared to another, both amplitude and peak velocity will scale down, but duration and stiffness values will stay (roughly) the same. Figure 14 shows the amplitude and duration data (with velocity indicated as slopes) for NS and AS as measured for API and PTK, separately for upper lip and lower lip closing movements.

[Insert figure 14 about here]

For upper lip, NS showed a clear increase in amplitude for PTK, but no change in duration; thus, peak velocity also increased (steeper slope). Clearly, a pattern fitting the amplitude scaling strategy depicted in 2 vs. 1 of figure 13. AS showed a slightly different change in movement parameters. First, the increase in amplitude was much stronger, but second, movement duration also decreased. Combined this led to a strong increase in upper lip peak velocity, something that was confirmed in the GROUP trends we found for these variables. Clearly, this pattern does not fit any of the strategies depicted in figure 13. Also notice that for upper lip, duration is longer for

API, but shorter for PTK compared to NS. However, amplitude is consistently higher for AS compared to NS in both tasks.

For lower lip data, NS showed a clear decrease in amplitude and a small decrease in duration for PTK, compared to API (this pattern is similar to the data for jaw and tongue body; see table 2). AS showed a similar trend, but stronger, and contrary to upper lip movements, the amplitude and duration values were only larger for AS compared to NS in the production of API. So, both NS and AS showed the type of control strategy depicted in the 1 vs. 4 contrast of figure 13.

A few conclusions can be drawn from this mass-spring model inspired comparison. First, control strategies for fluent speech in AS seem to more different from controls in her upper lip data, compared to the other articulators. Second, what is noticeable about AS's upper lip strategy is not an attempt to prolong movement duration, but to keep its amplitude relatively large across the two tasks (and this also applies to IPA; see table 2).

Why would this be relevant? To answer that question we need to turn to the lip coordination data. Here it was found that AS showed a trend for lower relative phase values in lip coupling across the three tasks. Data from a recent study suggest that lip coordination patterns are more stable when there is a greater lag between upper and lower lip movements (van Lieshout et al., 1999). Similar findings have been reported for people who stutter, based on larger and consistent time lags between successive moments of peak velocities for lips and jaw (van Lieshout, Alfonso, Hulstijn, & Peters, 1994). Relative phase values reflect stable solutions (or attractors) in the control network of articulators (Kelso, 1995; van Lieshout, 2004; Saltzman et al., 1989). Interestingly, the only kinematic variables that showed a consistent difference between AS and NS across all three tasks were upper lip amplitude and especially peak velocity,

both of which were higher for AS. It is possible that these higher amplitudes are associated with the stable lip coordination patterns found in AS's fluent speech data. This would certainly fit one assumption from Coordination Dynamics theory where it is stated that coupling stability can be influenced by critical thresholds in movement amplitude (and/or peak velocity), in addition to other factors (Peper & Beek, 1998). Recent data for speech provided some preliminary support for this claim (van Lieshout et al., 2002; Goozee, Lapointe, & Murdoch, 2002). More support can be gained from the data presented in part 2 of the current study. There it was shown that dysfluent speech samples are characterized by smaller gestural amplitudes and higher coupling variability. The decrease in amplitude could already be seen in the 1-second fluent speech samples before the onset of errors, but at that time coordination was still stable, indicating that in line with Coordination Dynamics, a switch to instability requires certain critical thresholds, not just a linear downscaling (e.g., Williamson, 1998; Beek, Peper, & Daffertshofer, 2002; Kelso et al., 1998; van Lieshout, 2004). In other words, amplitude/peak velocity changes may provide a (non-linear) window into the stability of coordination (van Lieshout, 2004).

We were somewhat surprised that AS in fluent speech showed little evidence for making adaptations to inter-gestural coordination, as opposed to intra-gestural coordination. This could be due to restrictions on allowable phase couplings at this level as evidenced by apparently distinct phase regions for inter-gestural coordination (see also Saltzman & Byrd, 2000). If true, this could mean that strategies to effectively control coordination stability are more easily implemented at the lower levels of coordination (intra-gestural), which in turn could benefit higher levels of coordination as well. As the data of part 2 indicated, AS' fluent and dysfluent speech do show clear differences in coupling stability for inter-gestural coupling, consistent with the coordination problems described in the literature (see introduction). This also demonstrates

that a clear separation between fluent and error-based speech samples (as described in this study) is necessary to tease out the source of kinematic and coordination changes (see also van Lieshout et al., 2004 for a similar discussion on stuttering).

Conclusions

In this investigation of the speech of a single subject with AOS and Broca's aphasia, we found that overall, her fluent speech was quite comparable to that of age-matched control speakers. However, when task constraints are taken into account, consistent kinematic differences appeared, together with differences in (intra-gestural) coordination. These differences seem reflective of a motor control strategy designed to maintain stability in movement coordination. The role of movement amplitude in this process was highlighted, including the apparent associative relationship between gestural amplitudes and coordination instability in comparing fluent and dysfluent speech samples. If these speculations about movement control strategies can be verified in future studies, this would provide a potential paradigm for treatment protocols that could benefit clinical populations, where changes in coupling dynamics can be experimentally induced by varying kinematic parameters like amplitude and/or peak velocities.

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Figure Captions

Figure 1. Simplified diagram of the general layout of the Articulatory Dynamics Theory (ADT) model, showing hierarchical layered levels of coordination (gestural score, tract variable, & articulators). The signals show kinematic manifestations of these levels, based on real data. See text for more details.

Figure 2. Example of a typical PTK trial-set for one control subject, with position information for the three gestures tongue body (TB), tongue blade/tip (TT), and bilabial closure (BC), as well as for the vertical dimension of the upper lip (uly), lower lip (lly; corrected for jaw), and Jaw (jwy). The rectangular shape depicts the virtual gestural boundaries (based on BC) for a single repetition of the task. Approximate “target” locations for individual sounds are also labelled (see text for more details).

Figure 3. Example of a cSTI analysis for the same upper lip and lower lip data as used in figure 2, showing both the original and filtered signals (as used for the analysis) in the top panel, and the individual cycle specific information (original, amplitude & time normalized). See text for more details.

Figure 4. Example of a cross-spectral analysis for TB and BC signals for the same trial-set as used for figure 2. The graph shows a strong frequency entrainment (correlation of 1) in the cross-spectrum panel for the dominant spectral peak at 2.8 Hz. See text for more details.

Figure 5. Example of a relative phase signal for the same tongue body constriction (TB) and bilabial closure (BC) gestures as shown in figure 2 at the dominant frequency of 2.8 Hz, depicted in figure 4. For this example, the coupling is very stable ($SD = 6.03$ deg) at 271 deg. See text for more details.

Figure 6. Example of a coded AS trial-set for IPA, with ‘1’ indicating normal fluent parts, ‘2’

parts immediately preceding sections with dysfluent speech samples, and ‘3’ parts containing dysfluent speech samples (as determined both acoustically and perceptually). The grey arrows identify gestural events associated with vowel position for /i/ and /a/, and bilabial closure for /p/.

Figure 7. Mean and standard deviations for the average length (in seconds) of within-trial set fluent speech parts for AS and NS, separate for task. See text for more details.

Figure 8. Normalized distribution identifying upper (+2.2 SD NS) and lower (- 2.2 SD NS) limits, outside which a main comparison between AS and NS would have led to a significant main GROUP effect. Individual mean values of AS are plotted appropriately within this range to assess how they fit the variation in the control group (NS). See text for more details.

Figure 9. Means and standard deviations for tongue body (tby) duration (DUR) and VPP values, separately for TASK and GROUP. See text for more details.

Figure 10. Means and standard deviations for intra- and inter-gestural coordination data (relative phase or PHI), separately for TASK and GROUP. See text for more details.

Figure 11. Mean and standard deviations for amplitude, peak velocity and duration of gestural movements (BC, TB, TT), separately for the different speech sample selections, with ‘1’ indicating normal fluent parts, ‘2’ parts immediately preceding sections with dysfluent speech samples, and ‘3’ parts containing dysfluent speech samples. See text for more details.

Figure 12. Mean and standard deviations for relative phase and SD relative phase for gestural coupling, separately for TASK and fluency code (‘1’ indicating normal fluent parts, ‘2’ parts immediately preceding sections with dysfluent speech samples, and ‘3’ parts containing dysfluent speech samples). See text for more details.

Figure 13. Mass-spring model diagram and predicted movement control strategies according to changes in amplitude (1 vs. 2), duration (1 vs. 3), or both (1 vs. 4). See text for more details.

Figure 14. Mass-spring model representation of changes in amplitude, duration and peak velocity for AS and NS in upper lip and lower lip closing movements, comparing API with PTK. See text for more details.

Table 1. Results of the assessment battery for AS

Western Aphasia Battery Kertesz, 1982

	<u>Raw score / Total possible</u>	<u>Score/Rating</u>
Spontaneous Speech	14 / 20	7.0
Auditory Comprehension	176 / 200	8.8
Repetition	52 / 100	5.2
Naming	72 / 100	7.2
Aphasia Quotient		70.4
Aphasia Classification		Broca's aphasia

Apraxia Battery for Adults Dabul, 1979

Severity rating	Moderate
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Boston Naming Test Kaplan, Goodglass, & Weintraub, 1983

Score	29 / 60	Severe
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Verbal Motor Production Assessment for Adults *

Global motor control	14 / 15	93.3%
Oral-motor control	35 / 69	50.7%
Oral and speech sequencing	23 / 38	60.5%

Interpretation	Oral-motor control more severely affected than sequencing
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Limb Apraxia Battery (unpublished) Roy, Square-Storer, Adams, & Friesen, 1985

Intransitive limb gestures	6 / 8
Transitive limb gestures	1 / 6
Complex axial gestures	2 / 12

Interpretation	Ideomotor limb and axial apraxia
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* The Verbal Motor Production Assessment for Adults (VMPAA), Hayden & Square (experimental version); adapted from the Verbal Motor Production Assessment for Children (VMPAC; Hayden & Square, 1999), was given to assess the neuromotor integrity of the speech systems, to rule out the presence of significant dysarthria, and to determine the level of speech motor disruption (i.e., global motor, oral-motor control, and sequencing).

Table 2. Means (upper row) and standard deviations (lower row) for kinematic variables, separate for task and articulator; see text for more details.

		AS			NS		
		API	IPA	PTK	API	IPA	PTK
AMP	uly	3.69	4.15	5.61	2.79	2.84	3.54
		1.25	1.02	0.77	1.01	1.14	1.33
	lly	16.29	12.78	7.49	12.70	10.05	8.67
		3.33	3.08	2.46	5.28	3.00	2.16
	tby	17.94	15.02	11.06	14.39	13.06	8.64
		1.76	2.70	0.95	3.74	2.97	3.18
	jwy	11.39	7.32	3.43	7.18	5.07	3.81
		2.13	2.16	2.21	3.84	1.67	2.55
PV	uly	32.01	34.27	51.57	24.29	24.28	30.59
		12.32	8.36	7.69	9.14	9.98	12.85
	lly	110.12	106.47	69.91	105.65	89.51	90.34
		19.76	24.68	19.97	23.11	19.34	21.56
	tby	130.03	110.78	91.70	105.48	104.41	70.77
		11.64	22.27	9.39	25.88	26.34	22.49
	jwy	83.18	52.11	34.16	51.59	41.41	34.64
		11.97	13.90	18.50	21.58	12.35	19.80
DUR	uly	551.53	587.77	432.15	483.89	481.57	498.02
		65.78	55.27	60.77	140.55	146.08	144.96
	lly	577.08	616.09	432.07	514.55	492.71	464.51
		80.54	73.74	70.20	141.96	135.82	105.95
	tby	560.52	602.71	431.04	511.47	494.54	494.59
		79.30	82.71	72.44	143.22	139.95	153.47
	jwy	580.91	580.98	386.48	526.17	495.79	448.50
		80.63	58.79	111.84	137.71	134.42	151.83
STIF	uly	8.63	8.27	9.19	9.10	8.80	8.96
		0.96	0.43	0.26	1.72	1.77	1.52
	lly	6.84	8.43	9.44	8.83	9.16	10.61
		0.64	0.71	0.49	1.62	1.25	0.85
	tby	7.77	7.39	8.37	7.48	8.06	8.84
		1.48	0.52	1.01	0.93	1.16	1.65
	jwy	7.41	7.47	11.21	7.73	8.43	10.28
		0.69	0.88	2.15	0.95	1.07	2.06
VPP	uly	2.26	2.39	1.97	1.99	1.94	2.02
		0.19	0.19	0.24	0.19	0.32	0.23
	lly	1.81	2.50	1.88	2.06	2.11	2.33
		0.12	0.17	0.28	0.27	0.32	0.56
	tby	2.02	2.18	1.75	1.82	1.90	2.02
		0.18	0.17	0.18	0.24	0.26	0.47
	jwy	2.09	1.92	1.97	1.83	1.89	2.02
		0.18	0.16	0.29	0.25	0.23	0.46
VPS	uly	46.27	41.94	52.79	47.99	47.27	49.24
		9.09	4.76	2.83	5.96	7.11	6.71
	lly	52.74	59.00	53.73	50.14	58.58	54.36
		6.61	5.32	10.47	11.32	5.71	9.23

Speech Motor Control in Apraxia of Speech

CSTI	tby	44.14	49.28	45.87	47.33	47.89	44.24
		5.47	6.30	1.34	5.26	5.63	7.33
	jwy	56.56	45.56	44.95	52.84	49.70	48.92
		5.20	8.98	5.24	6.87	8.11	3.60
	uly	5.58	4.41	6.08	10.73	11.02	8.78
		1.24	0.83	2.16	7.12	7.48	5.97
	lly	6.18	6.06	9.94	6.04	6.67	8.44
		1.31	2.20	2.42	1.82	2.06	3.51
	tby	6.51	4.82	6.85	6.14	6.13	11.82
		3.97	2.06	6.05	2.45	2.35	5.91
CV-PV	jwy	10.34	10.36	19.12	9.07	9.36	17.71
		4.07	6.50	6.89	5.03	3.15	6.30
	uly	0.17	0.11	0.08	0.21	0.21	0.19
		0.08	0.04	0.01	0.14	0.12	0.09
	lly	0.11	0.12	0.16	0.12	0.13	0.16
		0.02	0.04	0.03	0.04	0.04	0.08
	tby	0.13	0.09	0.14	0.10	0.10	0.18
		0.09	0.02	0.04	0.04	0.04	0.12
	jwy	0.13	0.20	0.33	0.15	0.19	0.27
		0.04	0.14	0.14	0.05	0.05	0.07

Table 3. Results repeated measures ANOVA for kinematic variables, separate for task and articulator; see text for more details.

		GROUP (A)		TASK (B)		A X B	
		df (1,7)		df (2,14)		df (2,14)	
		F	p	F	p	F	p
AMP	uly	5.1	0.058	18.91	0.001	3.278	0.068
	lly	0.8	0.401	12.71	0.001	1.98	0.175
	tby	1.59	0.247	193.36	0.001	2.18	0.15
	jwy	1.86	0.215	27.91	0.001	4.56	0.03
PV	uly	4.63	0.07	20.82	0.001	5.07	0.022
	lly	0	0.974	9.81	0.002	4.77	0.026
	tby	1.3	0.291	28.75	0.001	2.23	0.144
	jwy	2.39	0.166	21.48	0.001	5.14	0.021
DUR	uly	0.24	0.642	3.99	0.042	6.16	0.012
	lly	0.57	0.475	3.61	0.055	1.68	0.221
	tby	0.12	0.741	15.17	0.001	13.89	0.001
	jwy	0.13	0.725	7.72	0.005	2.17	0.151
STIF	uly	0.22	0.657	1.59	0.238	0.85	0.447
	lly	3.45	0.105	22.63	0.001	1.27	0.313
	tby	0.22	0.655	4.17	0.038	1.04	0.379
	jwy	0.04	0.845	24.81	0.001	2.03	0.168
VPP	uly	3.42	0.107	2.72	0.1	5.2	0.021
	lly	0.47	0.517	2.73	0.1	3.72	0.051
	tby	0.14	0.717	3.42	0.062	9.99	0.002
	jwy	0.53	0.489	0.43	0.657	1.13	0.35
VPS	uly	0.39	0.554	3.05	0.08	1.46	0.265
	lly	0.05	0.831	2.96	0.085	0.13	0.883
	tby	2.89	0.982	1.89	0.188	0.93	0.419
	jwy	0.51	0.45	7.51	0.006	2.09	0.161
CSTI	uly	1.67	0.237	0.12	0.889	0.91	0.427
	lly	0.18	0.688	4.52	0.031	0.47	0.634
	tby	2.47	0.16	9.42	0.003	4.1	0.04
	jwy	1.52	0.257	13.02	0.001	0.01	0.994
CV-PV	uly	1.95	0.205	1.96	0.178	0.96	0.406
	lly	0.01	0.917	1.77	0.206	0.06	0.945
	tby	0.28	0.614	4.14	0.039	0.91	0.425
	jwy	1.19	0.312	32.24	0.001	2.12	0.157

Table 4. Means (upper row) and standard deviations (lower row) for coordination data (intra- and inter-gestural); see text for more details.

	AS			NS		
	API	IPA	PTK	API	IPA	PTK
PHI-INTRA	145.51	193.13	121.87	165.87	209.70	183.49
	12.22	15.89	12.64	33.83	18.00	27.49
SDPHI-INTRA	4.92	5.96	7.68	6.68	7.72	6.32
	2.46	3.07	5.84	3.59	4.86	4.00

	AS				NS			
	API	IPA	PTK		API	IPA	PTK	
			<i>TB-TT</i>	<i>TT-BC</i>			<i>TB-TT</i>	<i>TT-BC</i>
PHI-INTER	42.98	260.08	49.53	153.93	71.13	290.98	55.33	150.36
	9.43	13.06	16.72	21.84	16.03	13.89	24.38	36.52
SDPHI-INTER	8.30	13.55	10.08	7.47	10.09	11.01	8.15	10.69
	5.80	5.81	3.95	3.98	2.95	3.83	3.40	4.23

Coordination Levels

Vertical = Amplitude
Horizontal = Duration