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10 Gesture production during stuttered speech: insights into the nature of gesture–speech integration

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1 Introduction

Some of our clearest insights into how the mind constructs language come from the investigation of challenges to the sensory, motor, and/or neural mechanisms of the human brain. The study of stroke and diseases of the central nervous system has led to enormous, but still incomplete, knowledge about the neural architecture of human language. Investigation of the sign languages that spontaneously arise among individuals who are deaf has revolutionized psycholinguistic theory by demonstrating that human language capacity transcends sensory and motor modality. The studies we describe here follow in this long research tradition.

We have been investigating the gesture-speech relationship in individuals with chronic stuttering in order to gain insights into the nature of the relationship between the two in spontaneous expression. Stuttering, the involuntary and excessive repetition of syllables, sounds, and sound prolongations while speaking, is highly disruptive to the production of speech. This provides us with an opportunity to observe what happens to the temporal patterning of gesture against the backdrop of a fractionated speech stream. Our studies have garnered striking evidence that gesture production is, and moreover must be, integrated with speech production at a deep, neuromotor planning level prior to message execution. The expressive harmony of gesture patterning relative to speech patterning is so tightly maintained throughout the frequent and often lengthy speech disruptions caused by stuttering that it suggests a *principle of co-expression* governing gesture–speech execution (Mayberry, Jaques & Shenker 1999). Before describing the research that led us to these conclusions, we briefly discuss some current hypotheses as to how gesture and speech are related to one another in extemporaneous expression.

2 The gesture–speech relationship

Exactly how gesture and speech are related to one another during the act of spontaneous expression is not fully understood, and there are competing hypotheses as to what the nature of this relationship is, or indeed, if there is a relationship beyond coincident production. One hypothesis holds that gesture and speech are autonomous and separate communication systems (Butterworth & Beattie 1978; Butterworth & Hadar 1989; Feyereisen & deLannoy 1991). In this hypothesis, which we call the 'independent systems' framework, gesture functions as a backup or auxiliary system for the temporary absence or failure of speech, such as in coughing, having a mouth full of food, or being unable to put words to thoughts. The hypothesis requires speech to fail in order for gesture to appear in the speech stream. Note that this hypothesis implies that there are links of a feedback nature between speech production and gesture such that when speech fails or is about to fail, gesture begins. With respect to stuttering, the independent-systems hypothesis predicts that stuttered speech will be accompanied by *more* gestures than will fluent speech. This would be due to the frequent failure of speech production during stuttered speech and relative lack of failure during normally fluent speech. This is because gesture is hypothesized as compensating for speech breakdown.

A related hypothesis (Goldin-Meadow, McNeill & Singleton 1996) proposes that gesture serves a compensatory role for speech, as exemplified by the home sign gestures of deaf children and the related phenomenon of sign languages. This proposal, unlike the independent-systems hypothesis, focuses on the compensating role gesture plays in the complete absence of speech, as in profound deafness. This is clearly not the case in stuttering, however, where speech remains the primary mode of expression. Nonetheless, stuttered speech can severely restrict spoken expression and sometimes halt speech for very long intervals. The question we address in our studies is whether gesture compensates for speech when speech is present but its expression is difficult.

An alternative hypothesis is that gesture and speech together form an integrated communication system for the single purpose of linguistic expression (Kendon 1980; McNeill 1985, 1992). In what we call the 'integrated system' framework, gesture is linked to the structure, meaning, and timing of spoken language. Thus, speech and gesture would always be co-expressed. With respect to stuttering, the integrated-system hypothesis predicts that stuttered speech will be accompanied by fewer gestures than

fluent speech, so long as the stuttered speech results in appreciably less spoken language content.

Investigating the nature of the gesture-speech relationship in terms of the production timing of gesture and speech in fluent speakers has led to findings that have been interpreted as supporting both the independent-systems hypothesis and the integrated-system hypothesis. For example, Levelt, Richardson & La Heij (1985) examined the relationship between voice onset time and the gesture apex (the movement extension of a point gesture) in subjects who were asked to point at a series of lights while simultaneously saying, "That one" or "This one" in Dutch. Gesture apex and voice onset time were found to co-vary with one another by a matter of milliseconds across a variety of conditions. When gesture production was hampered by putting weights on the hand, speech did not stop so long as the gesture interruption occurred within milliseconds. The time limit corresponded closely to the reaction time of saying a word. When the weight was placed after this time limit, speech halted. These findings were interpreted as showing that once word production was initiated, it could not be stopped even though the gesture was halted and thus as providing evidence for an autonomous view of speech and gesture.

In another study, Morrel-Samuels & Krauss (1992) found gesture movement to precede the co-expressed speech in English by milliseconds as a linear function of the lexical familiarity of the word or phrase being spoken simultaneously. Duration of gesture movement was likewise highly correlated with gesture–speech execution asynchrony. These findings were interpreted as supporting the integrated-system hypothesis.

Despite different interpretations, the basic findings of these studies were similar. Except when hand movements were impeded, the timing of gesture and speech execution were highly correlated with one another. Gesture and speech execution occurred within milliseconds of one another in a principled fashion, even though the execution of gesture and speech was not precisely simultaneous, which would be an unrealistic expectation given the gross differences in the articulators and motor systems involved: the vocal tract versus the upper torso, hands, and arms. Nonetheless, ambiguity remains as to the degree to which gesture and speech are linked in extemporaneous expression or, conversely, whether the appearance of being linked is an illusion caused by the fact that both modes are expressing similar meanings within the same time frame and communicative act.

We turned to the speech disorder of stuttering to shed light on this question (Mayberry, Jaques & DeDe 1998; Scoble 1993). In stuttering we can observe gesture production in the context of a highly disrupted speech stream. If gesture and speech are fundamentally linked in a deep way at the level of message planning as well as at the level of production, then gesture should keep full pace with stuttered speech, just as has been observed for fluent speech. However, if gesture and speech are truly autonomous and only appear to be synchronous because both modes are expressing similar meanings at the same time, then gesture production would be expected to break away from speech production during the highly extended stuttering blocks associated with chronic stuttering. Our experiments were designed to test these competing hypotheses and predictions. Before describing these studies, we give a thumbnail sketch of stuttering.

3 Stuttering

Stuttering is a speech disorder of unknown etiology that affects approximately 1 percent of the population. It usually begins in childhood with a gradual onset between the ages of two and five; 80 percent of childhood stutterers spontaneously recover (Bloodstein 1993). Stuttering appears to be sex-linked, affecting more males than females, at a ratio of 3:1 and tends to run in families. Both these facts suggest a strong heritable component to stuttering (Smith 1990). Stuttering does not dart randomly in and out of the speech stream, however. To the contrary, research has found that the appearance of stuttering in speech shows a systematic relationship to language structure: first sounds and syllables of words are more likely to be stuttered, as well as the first words of sentences and clauses, and content words as contrasted to closed-class words (Wingate 1988). The patterning of stuttering with the structure of language and speech appear to reflect neuromotor planning junctures where the information and coordination load is the highest for the central nervous system and hence the most vulnerable to breakdown in the speaker with a fluency disorder.

No previous studies have investigated the speech-related gestures of individuals who stutter, perhaps because gesture has traditionally been thought to fall outside the domain of speech and hence outside the domain of the disorder. A few studies have investigated the effects of stuttering on what has been called non-speech behavior, or more specifically, head, eye, and lip movement (Schwartz, Zebrowski & Conture 1990). Conture & Kelly (1991) note in passing that the hand may freeze in association with stuttering but give no other details. This observation is one of the effects of stuttering on speech-related gesture that we discovered and describe below.

4 Gesture in fluent and disfluent speech

In our first study, we adapted the experimental paradigm used by McNeill (1992) and his colleagues to elicit extemporaneous speech and gesture, the cartoon-narration task. We used an animated cartoon and, to avoid any

memory problems that might potentially be associated with having to narrate an entire cartoon, divided its presentation into three equal segments with respect to duration and the number of action episodes contained in each segment.

Subjects were tested individually. They viewed the first segment of the cartoon and then narrated the story line to an unfamiliar, neutral listener. By neutral, we mean that the listener made no comments other than "Anything else?" and produced *no* gesture. This procedure was repeated two additional times. The subjects' narration was videotaped and then transcribed. After the cartoon-narration task, the subjects who stuttered were asked to complete a brief protocol of reading, speaking on the phone, and speaking spontaneously. These tasks are standard clinical procedures for measuring stuttering severity (Johnson, Darley & Spriesterbach 1963).

Twelve English-speaking adults participated in the first study. Six subjects identified themselves as stutterers and had a childhood onset of the speech disorder. Five subjects were males and one was female; they ranged in age from 21 to 51 years, with a mean of 36 years. The stuttering severity of the subjects, as determined from a speech sample of one hundred words taken after completion of the first study, was mild for two subjects (0 to 5% of words stuttered), moderate for two subjects (5% to 10% of words stuttered), and severe for two subjects (greater than 10% of words stuttered). Six additional subjects with no history of stuttering were matched by age, sex, and highest level of education to the subjects who stuttered. The highest level of education for four of the subjects who stuttered was an undergraduate degree, and for two others it was a high school diploma. Likewise, four of the control subjects had an undergraduate degree, and two controls had a high school diploma.

We transcribed the narrations of the second and third segments of the cartoon for each subject. These were transcribed and coded for gesture, speech, and the temporal concordance between the two, always in the same order for all subjects. To ensure the validity of our transcriptions, the gesture transcription was completed first without reference to speech, i.e., with the audio portion of the videotape turned off. Each instance in which the subject moved his or her hand/s from rest to action was noted and categorized into one of three categories: (1) a self-touching movement or manipulation of an object, (2) a non-representational beat – moving the hand up and down – or (3) a representational gesture – gestures where the movement and/or hand shape is iconic, as in using a grabbing hand with a downward stroke to depict a woman 'swatting' a cat with an umbrella, or metaphoric, as in sweeping the hands across space to signify that the cartoon ended. The first category, self-touching and object manipulation, was analyzed no further because it was not considered to be gesture. The gesture coding was based on a coding system previously developed for sign language research (Mayberry & Eichen 1991). During the production of gesture, the hand/s sometimes made more than one gesture before returning to rest, as in making a 'swatting' gesture immediately after a 'grabbing' gesture. Thus, the number of gestures produced within each gesture unit was noted also, following conventions we had developed to measure and count morphology in American Sign Language (Mayberry & Eichen 1991).

In a similar fashion, we made the speech transcription without reference to gesture, i.e., with the video portion of the videotape turned off. The transcript included all words spoken in addition to all speech disfluencies. Each disfluency was categorized as being one of two types: (a) stuttered disfluencies, which included sound and syllable repetitions and audible and inaudible sound prolongations, or (b) normal disfluencies, which included word and phrase repetitions, word and phrase revisions, pauses, and interjections, such as "um" or "uh." The number of words, clauses, and cartoon story-line details the subject gave in his or her spontaneous speech sample was also noted.

Finally, we ascertained the temporal concordance between gesture and speech by combining the previous two transcripts with reference to both the audio and video portions of the videotape. The boundaries of each gesture were demarcated with respect to the words and disfluencies that were simultaneously produced with it. Gesture onset was defined as initiation of the hand/s' movement from rest; gesture offset was defined as movement cessation when the hand/s returned to rest. The precise temporal locus of each speech disfluency was determined as co-occurring with one of six sequential phases in gesture production taken from Kendon (1980) and Kita (1993): (1) the preparatory stage (raising the hand in order to execute a gesture), (2) the pre-stroke hold (an optional pause before initiation of the gesture movement), (3) the gesture onset (the initiation of gesture movement), (4) the gesture stroke (the movement of the gesture itself), (5) the post-stroke hold (an optional pause before returning the hand to rest), and (6) retraction (return of the hand to rest). Owing to the brief nature of beat gestures in contrast to representational ones, our analyses here are primarily concerned with the latter gesture type.

When we analyzed the fluency of the speech uttered by the two groups, we found, as expected, that the main difference between the two groups was the amount of stuttered disfluency that appeared in their speech and not the amount of normal disfluency. Stuttered versus normal disfluency turns out to be an important distinction when investigating the gesture–speech relationship, as we shall later explain.

Although the narration task was open-ended in the sense that the subjects could speak for as long as they wished, there was a strong effect of

stuttering on the length and content of the subjects' narrations. The control subjects said on average about 35 percent more words in 50 percent less time than did the subjects who stuttered. These findings underscore the fact that chronic stuttering renders the production of spoken expression difficult.

The difficulty stuttering imposes on spontaneous expression was also shown by a significant negative correlation between the degree of stuttering in the subjects' speech stream and the richness of narrative detail and complexity of sentence structure. Hence, the subjects who stuttered tended to give fewer narrative details with fewer clauses in simpler sentence structures (less embedding and complementation).

In keeping with the predictions generated by the integrated systems hypothesis, the reduced speech output of the subjects who stuttered was accompanied by only half the number of gestures produced by the control subjects in their narrations, with an average of 152 total gestures for the control subjects and an average of 82 gestures for the subjects who stuttered.

The reduced frequency of gesture expression that we observed in association with stuttered speech was not a simple function of less speech being uttered on the part of the subjects who stuttered. This was apparent when we examined the percentage of words the subjects spoke that were accompanied by gesture. The controls accompanied 78 percent of their words with gesture, but the subjects who stuttered accompanied only 30 percent of their words with gesture. This difference between the groups was also reflected in the amount of time that the subjects gestured, or, put another way, the amount of time that their hands were in the air while they spoke. The control group gestured for 70 percent of the total time they spoke, whereas the group that stuttered gestured for only 20 percent of the time they spoke.

The interruptions of stuttering on speech production have a clear attenuating effect on spontaneous expression with respect to linguistic content and structure: less is said in simpler sentences in more time than is typical of fluent speech. The gesture that accompanies stuttered speech, rather than compensating for reduced content and structure, shows an even more marked reduction than does the speech. Stuttered speech is accompanied by even fewer, and not more, gestures than fluent speech, with simpler forms and meanings (Mayberry et al. 1999). Thus we see that stuttering attenuates gesture production above and beyond what would be expected given the reduced speech content and structure. This suggests that some factor above and beyond 'amount of talk' affects the degree to which individuals who stutter gesture. Indeed, we have observed pre-adolescent children with severe stuttering not to move their hands at all on this narration task, something we have never observed in normally fluent children. Clearly much more research is required to investigate this complex finding. Next we examined the timing relationship between gesture production and fluent and stuttered speech.

5 Gesture is co-produced with fluent but not disfluent speech

We located all instances of normal and stuttered disfluencies in the speech stream of the subjects' narratives and then determined whether or not gesture was co-produced with each disfluency. This analysis showed that the normal disfluencies of the control subjects and those who stuttered were co-produced both with and without gesture with equal frequency.

In contrast to the maintenance of the gesture-speech relationship we observed for normal disfluencies, gesture was rarely co-produced with stuttered disfluencies. In the very few instances when a gesture was co-produced with a stuttered disfluency, the gesturing hand could be observed to fall to rest during the moment of stuttering and then to rise again and resume gesturing within milliseconds of resumption of speech fluency. In a few instances, the gesturing hand could be observed to stop moving during the moment of stuttering and to resume movement within milliseconds of the recovery of speech fluency. In fewer instances still, the hand began to gesture but abandoned the gesture by falling to rest and remaining at rest throughout the remainder of the spoken clause. These observations provide strong support for the integrated-system hypothesis and are not predicted by the independent-systems hypothesis.

In order to more closely examine the precise timing relationship between gesture execution and type of speech disfluency, we located every instance in which either a normal or a stuttered disfluency co-occurred with a representational gesture. We chose representational gestures for this analysis because the duration of representational gestures was of sufficient length to observe precisely the relationship between the motor-execution phase of the gesture and the speech disfluency with a high degree of accuracy without instrumentation.

The results of this analysis showed that stuttered disfluencies, that is, syllable and sound repetitions and prolongations, almost never co-occurred with the onset of the gesture stroke. By stroke onset, we refer to the movement-initiation point of a representational gesture that occurs after the handshape of the gesture is positioned in the air. This is in direct contrast to the normal disfluencies of both the control subjects and those who stuttered. The distribution of normal disfluencies for both groups occurred with comparable frequency across the pre-stroke, stroke-onset, and stroke phases of gesture execution.

In direct contrast, stuttered disfluencies occurred after the stroke onset of the gesture, toward the end of the gesture (that is, during the gesture movement and retraction phase). There was a marked absence of stuttered disfluencies at the stroke onset; no stuttering disfluencies accompanied the stroke onset. Four stuttered disfluencies occurred at the preparation phase of the gesture. In three instances the gesturing hand froze in midair during the stuttering bout and resumed moving only when fluent word production resumed after the stuttering bout ended. In one instance when a stuttering bout began during the preparatory phase of a gesture (raising the hand from rest), the hand immediately fell to rest and remained there throughout the stuttering bout. When the stuttering bout finally ended and fluent speech resumed, the hand immediately flew from rest and executed the stroke of the representational gesture in temporal co-expression with the now fluently produced word.

The same general tendency characterized the relationship between beat gestures and disfluency. However, six out of forty-seven beat gestures were executed simultaneously with the onset of stuttering disfluency, whereas no representational gestures were, so far as we could ascertain with the naked eye. Thus, there is a preliminary suggestion that the onset of the movement (or stroke) of a representational gesture requires fluent word production and beat gestures less so. A more detailed examination of this question is required with instrumentation, because beat gestures can be executed very quickly with much briefer duration than representational gestures.

One striking example illustrates the phenomenon well. One man who stuttered was narrating a cartoon sequence where the character Tweety Bird runs across a road. His spoken clause was "ran across the road," and his representational gesture accompanying the clause indicated a 'movement across a flat surface' (the palm, with straight and closed fingers, was face down and moved back and forth from in front of the torso outward). The man began to stutter on the word "ran" with multiple repetitions of the initial phoneme /r/. Just prior to the stuttering bout, his hand had moved from rest and assumed a flat, closed handshape but had not yet initiated the gesture stroke – the back and forth movement indicating 'across the surface'. At the moment when he began to stutter on the word "ran," his hand froze in space before initiating its (to and fro) movement; his hand remained motionless in space throughout the prolonged stuttering bout. When finally the stuttering ceased and he fluently uttered the clause "ran across the road," his hand simultaneously unfroze and initiated the gesture movement (to and fro) completely and co-temporaneously with the fluently spoken clause.

These findings and observations suggest that there are at least two important features that underlie the initiation of gesture movement, or the stroke onset, in representational gestures. One feature is that initiation of the gesture movement, or the stroke onset, appears to be functionally equivalent to the onset of word production. This is suggested by the finding that gesture production can be interrupted by speech stuttering throughout the preparatory phases of gesture production up to the *initiation* of gesture movement, i.e., the stroke onset. Once the movement of the gesture has been initiated, stuttering no longer interrupts gesture production. The second feature indicated by these data and observations is that the onset of the gesture stroke appears to be directly linked to the onset of fluent word production. This is suggested by the finding that gesture production co-occurs only with fluent word production. Gesture production is halted during bouts of stuttering.

Normal speech disfluencies do not show this link to the stroke onset of representational gestures. One appealing explanation is that word and syllable production and stress and prosody patterns are all maintained throughout normal speech disfluencies – the 'ums' and 'uhs' and word repetitions that are common in fluent speech. During this type of speech disfluency, gesture flow proceeds mostly unaffected. Stuttered disfluencies, by contrast, disrupt the flow of speech. Words and syllables are fragmented, and stress and prosody patterns collapse. Gesture production ceases until the speech stream fluently resumes. Clearly, gesture production is linked to fluent word production. If our interpretation is correct, then we would predict that speaking conditions other than stuttering that disrupt the flow of the speech stream, particularly with respect to word production, would also disrupt gesture production.

The robust correspondence between fluent speech production and maintenance of gesture production suggests that gesture and speech are planned and integrated by the central nervous system at some point prior to their actual physical execution. Moreover, there must be multiple feedback links between gesture and speech throughout extemporaneous expression. In other words, gesture and speech are an integrated system in language production. When speech stumbles and stops as a result of stuttering, the hand always waits for speech so that the meanings being expressed by the hand in gesture always coincide with the meanings being expressed by the mouth in speech, even when the gesture must wait for a very long time. Gesture and speech production are clearly not autonomous. We believe that the implications of these findings are significant and discuss them in greater detail below after describing our second experiment.

6 Only speech-related gesture is disrupted by stuttering

As provocative as our results were, we needed to exclude a purely manual-motor shutdown explanation for the phenomenon. While it has been long observed casually that individuals who stutter do not move their hands and arms while stuttering (A. Smith, pers. com.), it was nevertheless essential for us to demonstrate that the absence of gesture during the stuttering moment was due to a co-expression principle that governs gesture and speech execution rather than to some underlying inability to move the hands and arms during stuttering. The stuttering blocks of some of the subjects were so prolonged and disruptive to speech that a naive observer could readily envisage that a massive motor shutdown was taking place at the moment of stuttering.

In order to rule out a purely motor-shutdown explanation for the phenomenon, we asked three subjects who participated in the first study to participate in a second one where they narrated a second cartoon under three dual-task conditions (Mayberry et al. 1999; Scoble 1993). In the first dual task, the subject narrated a cartoon and simultaneously pressed a button continually. In the second dual task, the subject pressed a button to signal that he or she was stuttering. In the third task, the subject took a pencil and wrote the word being stuttered. All three subjects were able to carry out the simultaneous tapping and signaling dual tasks with no apparent disruptions during moments of stuttering. Moreover, all three subjects gestured with the free hand while simultaneously speaking extemporaneously and tapping with the other hand! Only one subject was able to write the word being stuttered during the stuttering moment. This was because the stuttering blocks of this subject, but not the other two, were of sufficient duration to permit word writing.

These findings completely rule out the possibility that at the moment of stuttering hand and arm movement is not possible. Rather, individuals who stutter are fully able to execute manual, non-gesture motor actions during the moment of stuttering, but they do not execute speech-related gesture during the moment of stuttering. During the moment of stuttering, speech is not being executed, and gesture is not being executed either, but the hand can scratch the head and grasp a pen.

These findings indicate that gesture and speech are tightly linked in extemporaneous expression. Gesture and speech were always co-expressed in all our data sets despite the frequent and often lengthy interruptions caused by stuttering – interruptions as frequent as one out of every ten words ranging in duration from milliseconds to minutes. The fact that the temporal concordance between gesture and speech execution is always maintained throughout stuttered and fluent speech suggests that the complex neuromotor patterns of gesture and speech are coordinated and integrated prior to their production in extemporaneous expression. What might the mechanism of gesture-speech integration be? We now address this question.

7 The neuromotor coordination of gesture and speech

One hypothesis as to how movements originating from disparate motor systems are coordinated is the "Dynamic Pattern" perspective. In this theoretical framework, the coordination of movement of different limbs is thought to arise from interactions between oscillatory processes themselves rather than from central representations (Kelso, Tuller & Harris 1981).

Smith and her colleagues (Smith, McFarland & Weber 1986; Franz, Zelaznik & Smith 1992) have discovered that simultaneously produced cyclic movements of the mouth, arm, and fingers harmonize with one another during meaningless, non-linguistic motor repetition tasks. Movements of separately controlled motor systems (the mouth and the finger, for example) eventually come to be harmonized with one another and then are co-produced in cyclic coordination. Such a mechanism could be the means by which the gesture-speech co-expression principle is achieved by the central nervous system. If so, this would mean that, in addition, the cyclic coordination that harmonizes the complex motor patterns of the gesture system with those of the speech system is ultimately coordinated by and integrated with the output of the conceptual and linguistic systems.

Although we can observe cycles of oscillation for the mouth and finger while each is engaged in simply repeating a single action, it is more difficult to imagine what the underlying cycles are in speech and gesture production that become harmonized to such a degree that they become a single expression of gesture-speech. The concept is especially difficult to imagine if speech is, a priori, conceptualized as having a linear, sequentially organized form with one word following another, and gesture is conceived of as having a spatial, simultaneous form, with gestures being three-dimensional masses placed in various spatial arrangements. But of course this may not be the case at all.

Thus we ask, Where are the cycles of speech and gesture that become harmonized in gesture-speech co-expression? One candidate possibility raised by our observations of subjects who stutter and the research of McClave (1994) and Nobe (1996) is that the oscillatory cycles of speech are contained in the prosodic patterns of the speech stream and that the oscillatory cycles of gesture are contained in the stress patterns of gesture movement. Speech prosody clearly rises and falls and reflects, to some degree, both the clausal structure of spoken language and the foregrounding and backgrounding of discourse and conceptual structure. Gesture movement likewise clearly rises and falls in relation to elements in conceptual, discourse, and linguistic structure and harmonizes with speech prosody. One germane observation from stuttering and gesture production that supports

this hypothesis is that the onset of the gesture stroke was always produced concurrently with the onset of fluent word production. Stuttered disfluencies almost never coincide with the onset of the gesture stroke.

In the examples where the gesturing hand waits for fluent speech production, we observe that the onset of the gesture stroke requires a fully formed and intoned word in order for both the gesture stroke and the uttered word to be executed together within milliseconds of one another. These findings are in keeping with those of Morrel-Samuels & Krauss (1992), who observed gesture and speech execution to be coordinated within milliseconds of one another in normally fluent speakers of English.

The exciting possibility added by the "Dynamic Pattern" perspective of motor-control theory to an explanation of how gesture and speech come to be so highly coordinated is that the harmonizing of cycles of speech and gesture during motor execution requires no central representation to achieve this remarkable feat of elegant cross-modal coordination. Instead, the neuromotor coordination of gesture-speech can occur on-line as spontaneous expression is being constructed and produced. It is important to note here that yet a third (or more) process is being harmonized with the cycles of gesture and speech, namely, the meanings being expressed by narrative and sentence structure.

How is this type of information wed with speech prosody and gesture tempo? It is possible that speech prosody and gesture tempo are part and parcel of propositional meaning and not separate systems that have to be coordinated and integrated with language meaning. From the earliest of ages and stages of language acquisition, children produce gesture and speech in a synchronized fashion. For example, Masataka (2000) and colleagues have discovered that the babble of Japanese babies is more canonical, or syllable-like, when they simultaneously flap their arms/hands as compared with when they do not. Nicholadis, Mayberry & Genesee (1999) have found that very young children co-produce iconic gestures with speech propositions shortly after putting words together for the very first time, and not before. Thus, there is certainly developmental evidence suggesting that arm/hand movements and representational gestures are co-produced and synchronized with speech from the very beginning of language development.

The key elements required for gesture-speech harmonization in production by the "Dynamic Pattern" perspective are that both the speech stream and the gesture stream have oscillatory movement, or cycles. Tuite (1993) has proposed that a rhythmic pulse underlies gesture and speech production. This rhythmic pulse may be the harmonizing cycles of gesture and speech coordination within the framework of the dynamic-pattern perspective. Our observations of individuals who stutter has led us to hypothesize that stuttering disrupts and/or destroys the temporal cycles that organize the speech stream, as suggested by the sometimes flat prosodic patterns common in the speech of individuals who stutter. For example, one subject who stuttered was mostly fluent but spoke in a monotone. This subject produced scant gestures. Hence, oscillatory cycles in the speech stream (in the form of prosodic patterns) may be necessary to glue gesture production to speech. While only speculative at this point, our working hypothesis as to how gesture and speech are integrated and coordinated at a deep neuromotor level prior to execution explains the striking effects of stuttering on gesture production that we have observed and documented here and elsewhere (Mayberry, Jaques & Shenker 1999; Mayberry, Jaques & DeDe 1998; Scoble 1993). In current work, we find the same phenomenon to characterize the gesture-speech production of pre-adolescent children who stutter in comparison with children who are normally fluent (Scott 1999).

In summary, the results of our studies strongly suggest that gesture and speech production are governed by a deep principle of co-expression in extemporaneous expression. As previous research has discovered, the structure and content of gesture parallels the structural and semantic properties co-expressed in speech. Our work extends these findings by suggesting that a principle of co-expression produces the tight temporal relationship observed in gesture-speech expression. Gesture execution starts and stops in temporal lockstep with speech execution throughout and despite the highly frequent and sometimes massive interruptions caused by stuttering. The resistance of gesture-speech co-expression to temporal uncoupling during severe bouts of stuttering broadens our view of the expressive act. The speaker's mind coordinates the complex patterns of the gesture system (finger, hand, arm, shoulder, and joint neuromuscular patterns) and integrates them with the complex patterns of the speech system (orofacial, laryngeal, and respiratory patterns) while weaving all this together with the complex mental structures of thought and language. The integration and timing the mind produces are so highly coordinated that all these vocal and gestural actions appear as one seamless image in the same moment of expressive time.

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