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Hand, Mouth and Brain

The Dynamic Emergence of Speech and Gesture

Introduction

The past fifteen years have seen a resurgence of interest in ideas of embodiment, the claim that bodily experiences play an integral role in human cognition (e.g., Clark, 1997; Johnson, 1987; Sheets-Johnstone, 1990; Varela *et al*., 1991). The notion that mind arises from having a body that interacts with the environment in particular ways stands in stark contrast to the predominant view since the 'cognitive revolution' of the post-war years. Using the computer as a metaphor for describing the structure of the mind, this cognitivist tradition has viewed thought as a product of abstract mental symbols and the rules by which they are mentally manipulated.

The fundamental difference between the embodiment and cognitivist perspectives lies in the role ascribed to the body, its characteristics, and its interactions with the environment. From a cognitivist point of view, the body is an output device that merely executes commands generated by symbol manipulation in the mind; the properties and activities of the body are irrelevant. From an embodiment perspective, however, cognition depends crucially on having a body with particular perceptual and motor capabilities and the types of experiences that such a body affords. In other words, cognition is a product of the body and the ways in which it moves through and interacts with the world.

In this chapter, we examine the embodiment of one foundational aspect of human cognition, language, through its bodily association with the gestures that accompany its expression in speech. Gesture is a universal feature of human communication. Gestures are produced by all speakers in every culture (although the extent and typology of gesturing may differ). They are tightly timed with speech (McNeill, 1992). Gestures convey important communicative information to the listener, but even blind speakers gesture while talking to blind listeners (Iverson and Goldin-Meadow, 1998), so the mutual co-occurrence of speech and gesture reflects a deep association between the two modes that transcends the intentions of the speaker to communicate. Indeed, we believe that this linkage of the vocal expression of language and the arm movements produced with it are a manifestation of the embodiment of thought: that human mental activities arise through bodily interactions with the world and remain linked with them throughout the lifespan. In particular, we

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propose that speech and gesture have their developmental origins in early hand–mouth linkages, such that as oral activities become gradually used for meaningful speech, these linkages are maintained and strengthened. Both hand and mouth are tightly coupled in the mutual cognitive activity of language. In short, it is the initial *sensorimotor linkages* of these systems that form the bases for their later cognitive interdependence.

Our defence of this proposition proceeds in this way. First, we show from extensive neurophysiological and neuropsychological evidence that, in adults, language and movement are very closely related in the brain. The question then becomes: How did they get that way? To answer this question, we invoke principles of dynamic coordination to show how two mutually active systems can influence and entrain one another. We then apply these principles to the early development of the speech–gesture system. We argue from developmental evidence that the motor actions of hand and mouth are present from birth and evolve in a mutually interactive fashion during the first year. We demonstrate how, as infants learn language, the changing thresholds and activation of hands and mouth for communication lead to the tight, synchronous speech–gesture coupling seen in adults. Finally, we speculate on this developmental story for the understanding of embodied cognition.

Before we embark on the details of our proposition, we review the current thinking about the relations between speech and gesture.

The Relationship Between Gesture and Speech

Currently, there are three competing views of the relationship between gesture and speech. The first of these posits that gesture and speech are separate communication systems, and that any existing links between the two modes are the result of the cognitive and productive demands of speech expression (e.g., Butterworth and Beattie, 1978; Hadar, 1989; Hadar *et al.*, 1998; Levelt *et al.*, 1985). According to this view, gesture functions as an auxiliary 'support system' whose primary role is to compensate for speech when verbal expression is temporarily disrupted (e.g., by coughing) or unavailable (e.g., when the speaker is unable to put thoughts into words). Importantly, any feedback links between speech and gesture are unidirectional, moving uniquely from speech to gesture. The production of gesture is thus assumed to have no effect on speech production or the cognitive processes that guide it.

The second view, recently articulated by Robert Krauss and colleagues (e.g., Krauss, 1998; Krauss and Hadar,1999, Rauscher *et al.*, 1996), differs from the first in that it assumes the existence of reciprocal links between gesture and speech. However, these links are located at a specific point in the process of speech production: the phonological encoding stage (cf. Levelt, 1989), or the moment at which a word form must be retrieved from lexical memory. Krauss and colleagues have argued that when speakers encounter difficulty in lexical retrieval, the production of gestures activates spatio-dynamic features of the concept in question. This in turn activates the lexical affiliate of that concept in memory and leads to successful articulation of the word. In other words, while gesture and speech are viewed as a linked system, the connection is highly limited in scope, with gesture influencing speech processing to the extent that it provides for cross-modal activation of concepts at a moment of difficulty in word form retrieval.

The third view of the gesture–speech relationship has been put forth by David McNeill (1992). In McNeill's view, gesture and speech form a single system of communication based on a common underlying thought process. Gesture and speech are tightly connected to one another, and there are links between gesture and speech throughout the process of speech production, occurring at the levels of discourse, syntax, semantics, and prosody. From this perspective, gesture and speech co-occur during production because they are linked to one another and to the same underlying thought processes (even though each modality may express a different aspect of that thought). Any disruption in the process of speech production should therefore have an effect on gesture, and vice versa.

In this chapter, we are inspired by and expand upon this third view, that articulated by McNeill. In particular, we begin by reviewing evidence from studies of normal adults and those with brain injuries and neurological disorders indicating that these two modalities are indeed linked in all aspects of language production. We then ask the developmental question: Where did these links come from?

Neurophysiological Links Between Language and Movement

Four lines of research from neurophysiology and neuropsychology provide converging evidence of links between language and movement at the neural level. These studies have revealed that: a) some language and motor functions share underlying brain mechanisms; b) brain regions typically associated with motor functions (e.g., motor cortex, premotor area, cerebellum) are involved in language tasks; c) classical 'language areas' (e.g., Broca's area) are activated during motor tasks; and d) patterns of breakdown and recovery in certain language and motor functions appear to be closely linked in some patient populations. We review each of these lines of work in turn.

Common brain mechanisms for language and motor functions

Studies employing electrical stimulation mapping techniques have indicated that some language and motor functions may share common mechanisms in certain brain regions. In these studies, electrodes are inserted into the cortex of a patient under local anaesthesia. A small amount of electrical current is delivered to each electrode in turn, and the effects of this stimulation on the patient's behaviour are measured.

Results from a series of studies conducted by Ojemann and colleagues (see Ojemann, 1984, for a review) point to a common brain mechanism for sequential movement and language that appears to be located in the lateral perisylvian cortex of the dominant hemisphere. Ojemann and colleagues reported that stimulation of this region resulted in two distinct patterns of change in motor and language functions. The first of these occurred primarily at sites at the posterior end of the inferior frontal gyrus, where stimulation disrupted imitation of any type of orofacial movement and also inhibited speech production. The second occurred at sites more widely distributed throughout the perisylvian cortex, where stimulation disrupted mimicry of sequences of orofacial movements (but not single movements) and evoked disturbances in naming or reading. However, recent verbal memory was not hampered by stimulation at any of these sites. This is important because it suggests that the observed disturbances in language production and movement were specific effects of stimulation at these sites, and not simply the product of global perceptual or attentional disruptions that might be a general consequence of the stimulation procedure.

Such observations suggest that there may be a mechanism common to language and sequential motor tasks located in this area. One candidate for a mechanism underlying language production and motor sequencing is precise timing, which is essential for the kinds of rapid movements that are involved in both motor sequencing and language production (Ojemann, 1984). This is a particularly appealing notion if we view gesture production as a motor sequencing task that co-occurs with speech production. A common timing mechanism for language and movement could account for the fact that gesture and speech are tightly linked in time, with the stroke of the gesture being executed in synchrony with the semantically co-expressive word or phrase (McNeill, 1992).

Not only is there some evidence for common mechanisms for speech production and sequential movement, but there is also some indication that the hands and arms and the vocal tract may be represented in neighbouring sites in certain brain regions. Fried *et al*. (1991) used electrical stimulation to map the functional organization of the supplementary motor cortex (SMA) in a group of patients preparing to undergo neurosurgery for chronic epilepsy. The obtained patterns of somatotopic organization indicated that sites where stimulation elicited movements of the hands and arms were adjacent to sites where stimulation resulted in speech disruption. Thus, in one patient, stimulation at one site in the left SMA was followed by the patient's report of a strong urge to raise the right elbow. Application of a slightly more intense current at the same site elicited abduction of the right arm, but no speech difficulties. At an adjacent site (approximately 1 cm away), however, stimulation elicited speech arrest in the form of hesitation during a naming task, but no arm movement.

Interestingly, in transitional areas between neighbouring somatotopic representations, stimulation often elicited complex movements involving body regions represented in these adjacent regions. For instance, at a site that appeared to mark a transitional area between the hand/arm and speech representations described above, stimulation elicited both speech arrest and finger flexion of the right hand.

These results raise the possibility that the tight temporal co-occurrence between gesture and language may be the product of spreading levels of activation in neighbouring areas, such that when the portion of the region associated with speech production is activated, activity spreads to the neighbouring site associated with movement of the hand and arm. Patterns of co-activation may be influenced by a common precise timing mechanism in the lateral perisylvian cortex, resulting in the production of gestures that are highly synchronous with co-occurring speech.

Motor areas are involved in language tasks

Additional evidence for neurophysiological connections between language and movement comes from work demonstrating that brain regions traditionally known as 'motor areas' become active in language tasks that do not explicitly involve speech production. In the motor cortex, for example, there are high levels of EEG activity when adults are asked to read words silently from a video screen. Interestingly, patterns of activity are particularly high when the target words are verbs (Pulvermüller, *et al*., 1996).

Premotor regions are also closely involved. For instance, when Grabowski *et al*. (1998) examined patterns of PET activity in a task involving retrieval of words from various conceptual categories (e.g., animals, tools, persons), they found high levels of activity in the left premotor area, but only when the words to be retrieved were tool names. One interpretation for this pattern of findings is that verbs and tool names have a strong motoric component that is stored with the semantic features of the word, and that the motor affiliate of such words becomes activated during lexical processing and retrieval.

Even the cerebellum, the portion of the brain most closely identified with movement, participates in language functions. Petersen *et al*. (1989) presented a group of normal, right-handed adults with two word production tasks: a) a simple task, in which participants were only asked to repeat a visually-presented word; and b) a complex task, in which participants viewed a word, had to think of a different word associated with the use of the presented word, and then say the associated word (e.g., saying 'sew' when the presented word is 'needle'). While both tasks require a similar vocal response (i.e., saying a word), the complex task also required participants to generate a word association. To identify cerebellar areas that were active during word association, a method of subtractive data analysis was employed, in which motor activation obtained in the simple task was subtracted from activation patterns obtained in the complex task.

The simple task (saying a visually-presented word) activated an area in the superior anterior lobe of the cerebellum. Interestingly, this area is just lateral to those activated by movements of the fingers. The word association task, however, activated an entirely different area, the inferior lateral cerebellum. Significant activation was found in this area even after subtracting away the motor activity generated by word production. Moreover, activation of the inferior lateral cerebellum was localized to the right hemisphere, the side that projects to the left hemisphere and was dominant for language in these participants.

These findings point strongly to connections between the cerebellum and classical 'language areas' such as Broca's area. Indeed, such connections have been identified anatomically (Leiner *et al*., 1989; 1993). This cerebro–cerebellar loop consists primarily of cerebellar output connections, which are projected to the reticular formation and the thalamus. Via the thalamus, these cerebellar projections can reach areas of the frontal lobe. The loop is completed by projections from prefrontal areas that are sent back to the cerebellum. Within this pathway, there are additional connections between cerebellar regions and cortical areas that have been implicated in language processes. For example, the dentate nucleus of the cerebellum projects through the medial thalamus and into Broca's area. In addition, signals can be transmitted via Türck's bundle from an area of temporal cortex known to be involved in language to the pontine nuclei and then to the cerebellum.

Language areas are involved in motor tasks

In addition to evidence pointing to motor area involvement in language tasks, there is now growing indication that language areas are activated during motor tasks in which linguistic mediation (i.e., using language to guide movements) is unlikely. While there are many so-called 'language areas' distributed throughout the brain, we focus our review here specifically on studies that have examined activity in Broca's area, which is perhaps the best known of these sites.

The question of whether brain areas activated by motor tasks overlap with those activated during language tasks was addressed in an fMRI study conducted by Erhard *et al*. (1996). Twelve healthy, right-handed participants performed a series of motor tasks (random tongue movement, toe movement, complex instruction-guided finger tapping, and copying of displayed hand shapes) and a language task. As expected, there was activation throughout Broca's area during the language task. The striking finding was that portions of Broca's area were also activated during each of the motor tasks, particularly the two tasks involving hand movement (see also Bonda *et al*., 1994).

Perhaps even more impressive, however, is that Broca's area is even activated when individuals think about moving their hands. Krams *et al*. (1998) looked at changes in cerebral blood flow patterns that occurred when healthy adults were asked to copy sequenced finger movements. Participants either executed the movements immediately, experienced a short delay prior to movement execution, or simply prepared the movements without executing them. There was a significant change in blood flow in Broca's area (specifically in Brodmann's area 44) in the two conditions involving a relatively extended period of movement preparation (the delayed execution and prepare-only conditions) relative to the immediate movement condition. In other words, merely planning a sequenced hand movement was sufficient to activate a portion of Broca's area.

Thus, in addition to its well-documented role in language processing and production, Broca's area appears to be involved in some motor activities related to the extremities and facial areas. In our view, this is important because it points to a possible neural substrate for the link between gesture and speech. Specifically, Broca's area appears to play a critical role in the generation of coherent sequences of body movements. Such a mechanism (along with others controlling precise timing of the sort described above) may well be involved in the co-production of speech and gesture, which requires the generation of sequential movements that are precisely timed with one another.

Evidence from special populations

The notion that gesture and speech co-production may draw on common brain mechanisms is further supported by studies of patients with a variety of different linguistic and motor impairments. Here we review evidence suggesting that some motor functions (particularly movement sequencing abilities) tend to be compromised when language is impaired; that gesture production can improve language skills in aphasic patients; and that gestures are produced even when there is damage to motor systems and proprioceptive and spatial position feedback are lost.

In a classic study of motor functioning in patients with left- and right-hemisphere injury, Kimura and Archibald (1974) reported that relative to right-hemisphere patients, adults with left-hemisphere damage performed significantly worse on a task involving copying of meaningless hand movements (e.g., closed fist, thump sideways on table; open hand, slap palm down on table) and on a traditional test of apraxia requiring demonstration of the use of familiar objects (e.g., show how to use a cup) and production of familiar gestures on verbal command (e.g., show how to wave goodbye). Additional analyses revealed that the poorer performance of the left-hemisphere group could not be explained by general difficulties with hand movement or the presence of linguistic deficits in these patients.

It may be the case, therefore, that the speech disturbances and movement difficulties manifested by left-hemisphere patients in this study are the product of a more general impairment in the type of motor sequencing involved in speech and gesture production. Additional support for this conclusion is provided by analyses of patterns of spontaneous speech and gesture production in patients with left-hemisphere damage (Pedelty, 1987). Specifically, patients with Broca's aphasia (generally a product of damage to anterior portions of the language-dominant hemisphere) exhibit parallel interferences in speech and gesture. The speech of Broca's aphasics tends to be agrammatic, consisting largely of content-bearing 'open-class' words and relatively lacking in grammatical functors (articles, prepositions, and other structural words). With regard to gesture production, Broca's aphasics produce many imagistic iconic gestures, which convey pictorial content (e.g., holding the arms out and extended slightly to the sides, conveying information about the size of a box) and relatively few of the fluid, hand-waving gestures that are often used to mark relationships within a conversation (e.g., the rhythmic beats of the hand that are observed at the moment in which new information is introduced into a conversation). Thus, when language breaks down in aphasia, parallel deficits are found in gesture.

That impairment in motor sequencing may be a more general feature of language disturbance is suggested by work examining the motor skills of children with specific language impairment (i.e., impaired language skills in the face of normal cognitive abilities and hearing). Hill (1998) tested children with specific language impairment (SLI) on a standard motor development battery and the familiar and unfamiliar hand movement tasks developed by Kimura and Archibald (1974) described above. She reported two striking findings.

First, despite the fact that children with SLI did not have any documented motor difficulties and were not selected for the study on the basis of their motor development battery scores, over half of the children (11 of 19) obtained scores that fell within the range for a group of children with developmental coordination disorder (DCD, a diagnosis characterized by movement difficulties out of proportion with the child's general level of development). Normally, 6% of the population of children between the ages of 5 and 11 years are diagnosed with DCD (American Psychiatric Association, 1994). Second, children with SLI scored significantly worse than age-matched peers and like children with DCD on the two tests of representational gesture imitation (with and without objects). This pattern was apparent in the performance of every child in the SLI group, even those who scored within the normal range on the movement battery.

The fact that motor functions related to the production of gesture are impaired when language is compromised is consistent with two recent studies suggesting that some language functions in aphasic patients may be improved by gesture production and training. The principal hypothesis of these studies was that if the output systems of speech and gesture are overlaid on the same 'general cognitive/movement cerebral systems', then gesturing should help stimulate the verbal articulatory system.

In one study, Hanlon *et al*. (1990) examined the effects of gesture production on performance in a confrontation naming task in patients with severe aphasia following left hemisphere damage. Patients were presented with black and white photos of common objects and asked to try to name the objects while either pointing at the picture or making a fist. They found that pointing with the right hand significantly improved performance, compared to fisting the right hand or pointing with the left hand. This suggests that functional activation of the right arm in the production of communicative gestures may facilitate activity in left hemisphere areas involved in the naming task, which may in turn result in improved naming performance.

This type of gestural activity also appears to have an effect on language functions that lasts beyond a single session in the laboratory. In a study of a single patient with nonfluent aphasia, Pashek (1997) employed a training procedure over multiple sessions to provide extensive practice with naming line drawings of gesturable objects and actions (e.g., a comb, a cigarette, scissors, to knock). Some of the stimuli were presented with verbal plus gestural training (i.e., oral repetition together with production of an associated gesture with either the right or the left hand), while others were associated with verbal-only training (i.e., oral repetition alone). The issues of interest were how naming performance would compare over time for verbal plus gesture versus verbal-only items, and whether the effects of training would be retained over time.

At baseline sessions prior to the beginning of training, accuracy was consistently poor across items, with the patient naming approximately 30% of the items correctly. By the fourth training session, however, performance had improved substantially for items associated with gestures (85% and 70% correct for left- and right- hand gestures respectively), while accuracy for verbal-only items was 50%. By the end of the training period, accuracy was quite high for verbal-plus-gesture targets (90% and 85% for left-hand and right-hand targets respectively), but had dropped down to initial levels for verbal-only items. What is perhaps most impressive is that gains made in naming for verbal-plus-gesture targets were retained for six months post-training.

In short, the finding that gesturing stimulates language functions associated with naming tasks (e.g., word retrieval, verbal articulation) is consistent with the hypothesis that the output systems of speech and gesture may draw on underlying brain mechanisms common to both language and motor functions. Further support for this view comes from a recent case study of spontaneous gesture production by a single patient who, as a young adult, suffered an infection that led to the loss of all proprioceptive feedback and spatial position sense from the neck down (Cole *et al.*, 1998). Movements requiring precision and maintenance of postural stability were effortful for this patient, and thus one might expect to find a total absence of gesture under these extreme conditions.

Contrary to this expectation, the patient produced gestures, and continued to do so even when he could not see his hands and make use of visual feedback to control their movement. Moreover, these gestures were tightly synchronized with speech, even when visual feedback was not available. Despite the fact that movements requiring spatial accuracy were virtually impossible for this patient, he was able to use space to differentiate meanings conveyed in gesture (e.g., a movement executed on the right side to represent one meaning, another on the left for a contrasting meaning).

These observations are striking because they indicate not only that gestures can occur in the absence of visual monitoring and proprioceptive feedback, but also that the gesture-speech relationship remains temporally and semantically intact even when other types of motor activities (e.g., walking, reaching) have been severely disrupted. This is consistent with the notion that the speech-gesture system is controlled by common brain mechanisms. Thus, even when there is damage to motor control systems, gesture may remain relatively spared because it is controlled at least in part by systems related to language that are distinct from traditional 'motor areas'.

In summary, a body of evidence from electrical stimulation, neuroimaging, and behavioural studies of healthy adults and patient populations is consistent with the view that gesture and speech form a tightly coupled system. Tasks requiring precisely timed movements of the vocal tract and hands and arms appear to share common brain mechanisms; classical 'language areas' in the brain are activated during motor tasks, and vice versa; subtle motor deficits, particularly in the production of sequential movement, co-exist with language breakdown and disorder; and gesture production appears to have a facilitating effect on language recovery. The strength of the coupling between gesture and speech is further underscored by preliminary findings indicating that spontaneous gesture production occurs even in the face of damage to brain regions involved in motor control.

There is thus compelling neurophysiological evidence suggesting that in adults, gesture and speech are inextricably linked in the brain. In the next section of this chapter, we argue that the foundations of these linkages are in place from birth, likely with phylogenetic origins. Furthermore, the gesture–speech system in adults can be understood as the product of the mutual, interacting development of these two systems over the first few years of life. We view this developmental pathway from the perspective of dynamic systems theory, and in particular, the principles derived for understanding the coordination of human movement. Our assumption here, based on the evidence we presented above, is that mouth and hand are two related movement systems that start out coordinated with one another and remain so, although the nature of the coordination changes. Thus, contemporary formulations of such coordination can be applied. We discuss limb coordination and then suggest that the same principles apply to the heterogeneous systems of mouth and hand.

The Dynamics of Motor Coordination

One of the central issues in understanding human movement is the question of coordinating the limbs and body to perform adaptive actions. How do people and other animals so precisely move their limbs in time and space to walk, run, or manipulate objects? Dynamic systems theory in motor control was initially formulated to address the problem of coordination of the limbs as a special case of the more general issue of coordination in complex systems (e.g. Kugler and Turvey, 1987). The principle tenet of a dynamic systems approach is that in such complex, heterogeneous systems (such as moving animals), the individual parts cooperate to form patterns, which exist in space and time. This cooperativity occurs without any 'executive' direction, but rather strictly as a function of the coherence of the parts under certain energetic constraints. Many such self-organized patterns occur in nature in physical and biological systems, with no 'cognitive' intervention (see Kelso, 1995).

The most well-studied phenomena are issues of coordination in rhythmic limb movements in humans and other animals. Rhythmic movements are universal in animal movement, primarily for locomotion, but also in humans for tool use, music, (and in speech and gesture!). The contemporary dynamic view rests heavily on earlier work by the physiologist von Holst, who studied locomotion in fish and insects. In particular, von Holst described the actions of fish fins as individual oscillators that were, however, coupled to one another. Von Holst enumerated several principles of this interlimb coordination:

(1) Each fin had a preferred frequency when acting alone.

(2) Sometimes the oscillation of one fin could be detected in the oscillation of another. This is the *superposition* effect.

(3) Each fin tries to draw the other fins to its characteristic oscillation. This is the *magnet* effect, and it results in a cooperative tempo, often a balance between the two competing tempos.

(4) Each fin tries to maintain its preferred frequency when participating in a coupling, leading to variations around the mean cooperative tempo. The *maintenance* effect illustrates the dynamic nature of the coupling of several oscillators: there is a tension between maintaining the preferred frequency and the strength of the entrainment to other oscillators.

These principles were best illustrated in human limb movements by experiments done by Kugler and Turvey (1987) over a decade ago. They examined the entrainment of rhythmical arm movements when they experimentally changed the arms' natural frequencies. Under normal circumstances, it is very natural for people to flex and extend their arms rhythmically about the elbows, either in phase or alternating. The comfortable frequency that people choose for the movement of the combined limbs is very similar to the natural frequencies that people find comfortable when swinging one arm alone. Kugler and Turvey asked people to do this simple movement while holding weighted pendula. People swinging heavy weights preferred a lower oscillation rate than those holding light weights. What happens when people are holding a heavy weight with one hand and a light weight with the other and they are asked to find a common rhythmical coordination pattern? The solution is just what von Holst predicted: they find a compromise frequency that is neither as fast as the light arm nor as slow as the heavy one. In short, these two coupled oscillators, represented by the two arms, mutually influenced one other to produce a single coordinated behaviour, synchronous in time and space.

We have shown that, in terms of their control, the speech articulators and the hands and arms are closely related. We suggest that, indeed, the systems activating mouth and arms can mutually influence and entrain one another, much as has been amply demonstrated for limb systems alone. Furthermore, we propose that these entrainments are dynamic and flexible such that activation of one system can have various effects on the other — tight temporal synchrony, or more loosely coupled influence — according to von Holst's principles above. We believe that this conceptualization of mutually influential systems can help explain the linkage between speech and gesture.

To begin to understand the initial hand–mouth linkages and the subsequent developmental changes that we describe, we propose a simple, qualitative model. Two concepts are critical: the notions of the *thresholds* for eliciting vocal and manual behaviours, and their *relative activation strengths*, and in particular, their ability to pull in and entrain the activity of the complementary system. The threshold for a behaviour measures its ease of performance: in naturally occurring behaviours seen in infants, a good measure is how frequently they are performed. Behaviours with a low threshold for performance are seen frequently and under different task contexts. Behaviours with a high threshold, in contrast, are effortful and less frequently produced. Thus, we assume that first gestures and words have a high threshold (as do first appearances of any new skill). One effect of repeated practice is to lower the threshold for performance, to make that behaviour available at different times and in different and variable contexts.

Activation is the relative strength of the behaviour once the threshold is reached. Because a great deal of effort is required in order for relatively novel, unpracticed forms of behaviour to emerge, we assume that new behaviours have relatively low levels of activation. In contrast, more established, well-practiced behaviours can be said to have relatively higher levels of activation; that is, they are strong, stable skills. A critical assumption is that the dynamic coupling of two effector systems — either limbs or limbs and oral structures — requires relatively high levels of activation in order for mutual entrainment to occur.

The Development of the Coupled Speech–Gesture System

We now put these ideas of coupled oscillators, thresholds, and activation together to describe the ontogeny of oral and limb movements leading to gesture and speech coupling. We propose a dynamic developmental progression characterized by four phases: 1) *initial linkages*: hand and mouth activity are loosely coupled from birth; 2) *emerging control*: increasing adaptive use of hands and mouth, especially marked by rhythmical, sometimes coordinated, activities in both manual and vocal modalities; 3) *flexible couplings*: emergence of coupled, but not synchronous gesture and speech; 4) *synchronous coupling*: more adult-like, precisely-timed coupling of gesture and speech. This progression is summarized in Table 1 and Figure 1. We now turn to a description of how the initial biases that link hand and mouth become progressively elaborated as language and gestural communication emerge and relate these changes to the model outlined here.

The early oral–manual system

Connections between the oral and manual systems are in place from birth (cf. Table 1). This link is initially apparent in the Babkin reflex: newborns react to pressure applied to the palm by opening their mouths. Moreover, coordination between oral and manual actions is extremely common in infants' spontaneous movements. For instance, newborns frequently bring their hands to the facial area, contact the mouth, and introduce the fingers for sucking, often maintaining hand–mouth contact for extended periods of time. Hand-to-mouth behaviour in young infants looks goal-directed. Infants bring their hands to the mouth in the absence of prior facial contact. They open their mouths in 'anticipation' of the arrival of the hand. The trajectory followed by the hand en route to the mouth varies widely from bout to bout, suggesting that they can attain mouth contact from many different starting positions (Butterworth and Hopkins, 1988).

Hand-to-mouth behaviour continues to be an important action throughout the first year, but the behaviour shifts in function. As soon as infants are able to grasp and hold objects placed in their hands, usually at two months, they bring these objects to their mouths and explore them orally (Lew and Butterworth, 1997; Rochat, 1989). Indeed,

Developmental period	**Evidence**	**Oral (speech)/manual linkages**	
Newborn: Initial linkages	Oral: Sucking, crying, vegetative sounds Manual: Hand to mouth/ reflexive grasping, spontaneous movements, no ability to reach	Babkin reflex Spontaneous hand/mouth coordination	Hand and mouth are mutually activated.
Six to eight months: Emerging control	Oral: cooing, sound play, reduplicative babbling Manual: Onset of reaching, rhythmical waving and banging, manual babbling	Onsets of rhythmical vocal and manual babbling, rhythmical arm movements coincide	Rhythmical activities in arms and hands and in speech articulators mutually entrained.
Nine to 14 months: Emergence of gestures and words	Oral: variegated babbling, onset of first words Manual: onset of first gestures, fine motor control in fingers improves	Communicative gestures precede first words; gesture use predicts first words. Gestures and speech have different referents. When gestures and speech co-occur, they are sequential.	Threshold for gestural activation lower than for speech. No simultaneous coactivation of speech and gesture because threshold for both is high, but entrainment activation is low.
16 to 18 months: Emergence of synchronous speech and gesture	More communication Increasing vocabulary Continued fine motor improvement	Onset of meaningful, synchronous word + gesture combinations	Practice with communication lowers thresholds and increases entrainment activation, leading to synchrony.

Table 1. Developmental progression of oral–manual linkages during the first two years.

when infants learn to reach out and grab objects on their own, they invariably bring these objects to their mouths, a behaviour that continues throughout the first year.

These hand–mouth linkages are also apparent in communicative settings. Fogel and Hannan (1985) observed a group of infants between the ages of 9 and 15 weeks during face-to-face interaction with their mothers and found systematic relationships between certain types of hand actions and oral activity. In particular, extensions of the index finger were especially likely to co-occur with either vocalization or mouthing movements.

Taken together, these observations suggest that discrete manual actions and oral or vocal activity are linked from birth and continue to be coupled in the first months of life, well before the emergence of first gestures and words. In terms of our dynamic model, they further suggest that thresholds for hand–mouth activity are relatively low and activation is high in the first months (cf. Figure 1). Instances of hand–mouth contact and co-occurrences of hand movements with vocalizations are seen frequently;

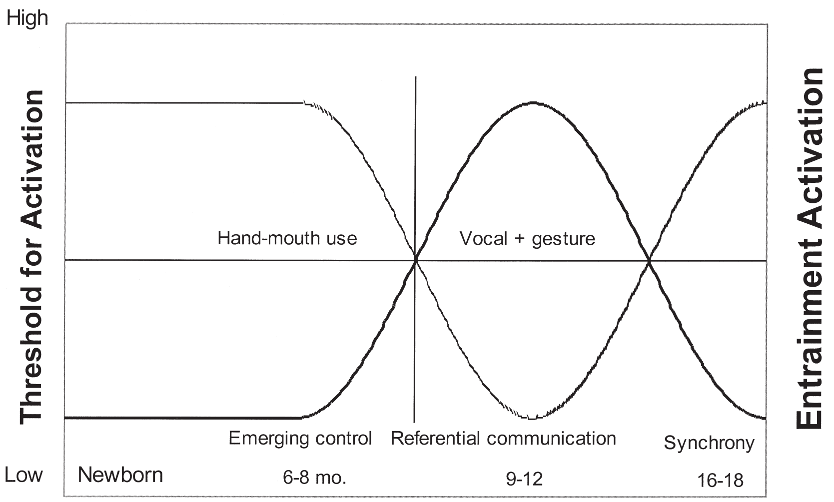

Figure 1. Threshold and entrainment activation levels in the oral–manual system during the first two years.

Initially, activation (depicted in the thick line) is high and the threshold (depicted in the thin line) is low and remain so until the emergence of referential communication. At this point, communication is a novel and effortful skill, and thus the threshold is raised and activation becomes relatively weak. As children practice their communicative skills, the threshold is lowered and the level of activation increases.

and infants tend to spend a substantial portion of their time with their hands in their mouths (Vereijken *et al.*, 1999). In short, there appears to be some degree of co-activation of the hands and mouth from very early in life, such that co-occurring manual and oral behaviours form a central part of the young infant's behavioural repertoire.

It is tempting to speculate that these initial hand–mouth linkages are phylogenetically established, possibly as the result of mechanisms that link manipulation and feeding. In non-human primates, for instance, manual dexterity is associated with food-gathering processes such as opening seeds, fishing for termites, and using tools to break shells and husks. This suggests that the speech–gesture linkages may be using brain systems that long predate human language and, indeed, may have evolved for completely different functional purposes. In this way, we echo Bates *et al.*'s (1979) claim that 'Language is a new machine that nature made from old parts'.

Reorganization of the oral–manual system and emerging control

At around three or four months of age, infants show increasing adaptive control of both the hand–arm and the oral–vocal systems (cf. Table 1). Visually-elicited reaching and grabbing objects emerges at this time, as does the ability to produce differentiated vowel sounds and cooing vocalizations, especially during social interactions. Although the manual and vocal systems appear to be developing relatively independently, there are also indications of continued coupling, and indeed, mutual influence.

Manual–vocal coupling is best evidenced in the production of *rhythmical movements* in both effectors. Rhythmicity is highly characteristic of emerging skills during the first year of life. Thelen (1981; 1996) has suggested that oscillations are the product of motor systems under emergent control; that is, when infants attain some degree of intentional control of limbs or body postures, but when their movements are not fully goal-corrected. Thus, for instance, infants commonly rock to and fro when they can assume a hands-and-knees posture, but before they can coordinate their four limbs for forward propulsion in creeping.

Rhythmical movements of the arms and hands — waving, swaying, banging — indeed increase dramatically between the ages of 26 and 28 weeks. This is several months after infants first reach, but before they develop differentiated use of arms and hands for manipulation. The emergence of canonical babbling (i.e., when babies begin to produce strings of reduplicated syllables, such as 'gagaga' or 'bababa'), which is also a rhythmic behaviour, occurs at about the same age, averaging about 27 weeks (e.g., Oller and Eilers, 1988). Most importantly, findings from two studies suggest that there is a close temporal relationship between the onset of babbling and changes in patterns of rhythmic hand activity.

The extent to which the emergence of babbling and changes in rhythmic hand and arm movements are temporally related was specifically addressed in a cross-sectional study of repetitive arm activity in infants who had either not yet begun to babble or who had been babbling for varying lengths of time (Locke *et al*., 1995). Infants were given a rattle to shake in either their right or left hand, and the overall frequency of shakes per second was recorded. Results indicated that rate of shaking was relatively low among prebabblers, increased substantially among infants who had just begun to babble, and then declined somewhat (but remained above that for prebabblers) among infants who had been babbling for longer periods of time. Importantly, the frequency of shakes was consistently higher for the right relative to the left hand across all infants, regardless of amount of babbling experience, suggesting that the sharp increase observed among new babblers cannot be explained simply by heightened arousal levels in this group of infants.

The assumption that the oral and manual articulators are tightly linked from birth and remain so also explains the recently described phenomenon of 'manual babbling' observed in both deaf and hearing infants. First described by Petitto and Marentette (1991), manual babbles are gestures that are neither communicative nor meaningful and tend to consist of more than one movement cycle. For instance, a child might extend the first finger of the left hand and repeatedly contact the palm of the right hand, while at the same time giving no indication that the movement is meaningful or directed toward a specific addressee. In other words, although the form of the movement may be gesture-like, the apparent absence of meaning and communicative intent make it difficult to classify as a communicative gesture. Petitto and Marentette interpreted manual babbling in deaf infants as a manual analogue of vocal babbling that is evidence of a dedicated, amodal language acquisition faculty.

More recently, however, Meier and Willerman (1995) recorded instances of manual babbling in hearing infants with no exposure to sign language. In a longitudinal study of two hearing infants, they reported that manual babbling co-existed with vocal babbling, and that manual babbles accounted for a majority of the children's manual output between the ages of 7 and 8.75 months. Based on these findings, they concluded that the manual babbling may not necessarily be an indication of a 'brain-based language capacity', but rather one of a class of rhythmic behaviours that emerge during the transition to more differentiated motor control. Thus, the period between about 6 and 9 months is one in which rhythmical and repetitive movements abound as transient patterns consistent with emergent fine motor control in both mouth and hand.

As we discussed earlier, it is well-known that biological oscillators tend to interact and entrain one another. Assuming an initial linkage of the mouth and hand subserved by the same brain systems, it is plausible that rhythmicity in the two effector systems is mutually influential. In our model, we see that this is also a period of low thresholds and high activation for rhythmical vocal and manual behaviours (cf. Figure 1); they are relatively common and often performed (see Thelen, 1979; Oller and Eilers, 1988, for frequencies). Given the combination of low thresholds and relatively high activation, our dynamic prediction is that these two systems should mutually entrain. Indeed, in a recent longitudinal study of Japanese infants, Ejiri (1998) reported that approximately 40% of all rhythmic manual activity co-occurred with babbling, and that 75% of all babbling co-occurred with rhythmic manual activity. Additional evidence of mutual entrainment comes from the finding that the average syllable length in bouts of babbling accompanied by hand activity was significantly longer than that in bouts that did not co-occur with manual actions (Ejiri and Masataka, 1999). This difference is illustrative of a principle of coupled oscillators that we described earlier, namely that two motor systems (in this case, the hands and the jaw) mutually influence one another and ultimately settle on a ‘compromise’ frequency at which they entrain to produce a coordinated behaviour.

We may speculate further that the development of vocal babbling is actually facilitated by early rhythmical limb movements. Infants have a long history of producing rhythmic arm, leg, and torso movements prior to the onset of canonical babbling. It is possible that production of repetitive, rhythmically-organized movements gradually entrains vocal activity, leading eventually to the production of the mandibular oscillations that comprise babbling. In short, to the extent that manual and vocal babbling are indicative of increased control over the manual and oral articulators, they may be transitional behaviours in the development of the speech–gesture system. The repetition of babbling activity in both modalities may then allow the child to gain further control over the oral and manual articulators, control that is clearly necessary for the production of first words and gestures.

Learning to talk and to gesture: the period of flexible coupling

In the last few months of the first year, infants’ manual and vocal behaviours change (cf. Table 1). Banging and waving decrease, and infants use their hands for more finely differentiated manipulation. Likewise, babbling gives way to words and word-like productions. This period also sees the emergence of communicative gestures such as pointing, showing, and requesting. As production of communicative gestures increases, beginning between the ages of 10 and 11 months and continuing through the first few months of the second year, manual babbles tend to decline (Meier and Willerman, 1995). Rhythmic repetition thus gives way to more articulated control and more directed communication.

Importantly, however, during this third transition, communication by gesture is predominant, while verbal communication tends to lag behind. For example, children often produce their first gestures several weeks before they say their first words (e.g., Bates *et al*., 1979; Caselli, 1990). In addition, gestures often outnumber words in the communicative repertoires of individual children at this stage, and many children show a strong preference for gestural over verbal communication in their spontaneous interactions (Iverson *et al*., 1994).

What does this transition tell us about the organization of the coupled speech–gesture system? In our model, this period is characterized by asymmetry in the relative control and activation of these effectors. At this time, gestures become increasingly frequent, while speech develops somewhat more slowly and is more effortful. Thus, relative to speech, for which thresholds are high and activation is relatively weak, well-practiced manual activities and gesture have lower thresholds and higher activation (cf. Figure 1). In short, we believe that the threshold for communication in the manual mode is much lower in late infancy than in the vocal mode, likely because control of the hands and arms is more advanced than that of the vocal articulators. If infants are motivated to communicate, it is simply easier for them to use movements that have been well-practiced in the service of object exploration. This is a well-known phenomenon of motor control, namely that stable and well-patterned movements are preferred over newer and less well-established coordinations (Zanone and Kelso, 1991).

Although gestures often play a predominant role in children's early production, the two systems are still tightly linked. Several observations provide support for this claim. First, gesture production can predict impending change in speech. Thus, for example, Bates *et al*. (1979) reported that gesture production was positively related to gains in language development between 9 and 13 months. In other words, children who made the most extensive use of gesture were also those who exhibited the most precocious language development.

Second, work by Acredolo and Goodwyn suggests that teaching typically-developing, hearing children to gesture has positive effects on language development (e.g., Goodwyn and Acredolo, 1993; 1998). These researchers asked parents to teach their infants a small set of communicative gestures and encourage them to use these gestures in daily interactions. Longitudinal data on the attainment of early language milestones indicated that these children produced their first symbols (i.e., a word or gesture that is used reliably to 'stand for' a referent, independent of context or proximity to the referent) and attained the five-symbol milestone approximately one month earlier than groups of children who had received no training or who had been taught a small set of words respectively.

A final piece of evidence comes from studies indicating that continued delay in the development of productive language may be predicted from gesture production. This research involves examining patterns of speech and gesture production in young children who are 'late talkers', a group generally characterized by delayed acquisition of productive vocabulary in the absence of hearing loss, mental retardation, behavioural disturbances, or known forms of neurological impairment. Thal and Tobias (1992) analysed late talkers' spontaneous speech and gesture production at an initial visit and at a follow-up one year later. By the follow-up visit, some of the children originally identified as late talkers had caught up with their peers in terms of their language production abilities (the 'late bloomers'), while others continued to show delays in expressive language (the 'truly delayed' children).

These investigators found that the late bloomers and the truly delayed children could be reliably distinguished from one another on the basis of their communicative gesture production at the initial visit. Thus, late bloomers produced significantly more communicative gestures than did truly delayed children, who looked more like a group of younger children matched on the basis of productive language. That reduced use of communicative gestures is related to delayed language development is further indicative of the coupled nature of the gesture–speech system; that is, when functioning in one part of the system is compromised, functioning in other components may also be disrupted.

The emergence of synchronous speech and gesture

As we mentioned earlier, gestures and speech are very tightly coupled in adults. When people talk and gesture at the same time, the 'stroke' (or active phase) of the gesture is timed precisely with the word or phrase it accompanies. This timing relationship is so strong that when a speaker stutters, the gesture tends to be held motionless until the speech is recovered (Mayberry *et al*., 1998).

This tight temporal link appears to develop during the initial period of gestures and first meaningful words (cf. Table 1). Butcher and Goldin-Meadow (in press) described patterns of relative timing of words and gestures in infants as they acquired early language. They found that at first, gestures tended to be produced without speech or with meaningless speech. Even when gesture and vocal utterances occurred together, they were not tightly linked in time. The gesture and the word or vocalization occurred sequentially, not simultaneously. Adult-like gesture–speech synchrony emerged rather dramatically when infants began to combine meaningful words with gestures.

This change in the timing relationship between gesture and speech can be accounted for in our model in the following way. During the time when infants are just beginning to acquire many new words, speech requires concentration and effort, much like the early stages of any skill learning. As infants practice their new vocal skills, thresholds decrease, and activation for words becomes very high (cf. Figure 1). Since the level of activation generated by words is well beyond that required to reach threshold, it has the effect of capturing gesture and activating it simultaneously. The behavioural result of this co-activation is a word–gesture combination in which the two elements are fully synchronous. In other words, as words are practiced, they are able to activate the gesture system sufficiently to form synchronous couplings, and thus the two motor systems become entrained. Thus, by the time infants are combining meaningful words with single gestures, speech is synchronously coupled with gesture, a coupling that remains tight throughout life.

Thus, we see the intensive period of word learning as the point at which initial oral/manual linkages are consolidated into a new organization that couples the emergent gesture system with the emergent speech system. It is the dynamics of change in the effort required for these early skills that provides the 'spill-over' activation needed to link the two effector modes in a common communicative intent.

Speculations on an Embodied Cognition

We have shown with converging evidence that systems of movement for mouth and for hand cannot be separated from one another, and that they are intimately linked in the production of language, the pinnacle of human cognition. We invoked concepts of coupled oscillators that hold that related systems can interact, mutually activate and entrain one another. We further speculated that during development, with initial linkages established phylogenetically through feeding systems, it is manual activity that acts as a magnet. Through rhythmical activity, and later through gesture, the arms gradually entrain the activity of the vocal apparatus. This mutual activation increases as vocal communication through words and phrases becomes more practiced, leading to tight synchrony of speech and gesture in common communicative intent.

What does this mean for a theory of embodiment? As language develops, its expression through speech is continually accompanied by movement, such that vocal behaviour is tightly intertwined with hand and arm activity. These movements co-occur with the communicative intent that produces them. Thus, every communicative act, either by speech or gesture is remembered as an ensemble, which includes the proprioceptive consequences of that movement. As utterances become common and frequently practiced, the motor repertoire that is mapped with the growing language competence also becomes strengthened. The initial biases to move hand and mouth together thereby cascade into a single coupled, communicative system, where the mental aspects of the expression are manifest in movement.

The speech–language–gesture system is a particularly compelling example, we believe, not only of the sensorimotor origins of thought, but also of its continued embodiment throughout life. In this chapter we showed that a model based on notions of coupled oscillators can explain the changing patterns of coordination of mouth and hand in the first years and their link with emergent language. The critical point for embodiment is that such coupling demands that the systems involved in speech, gesture, and language are represented in the brain in commensurate codes. That is, the representations of the mental aspects of language must be able to mesh seamlessly with those involved in the control of movements. Traditionally, language is viewed as symbolic and discrete, represented by lexical items and grammatical rules. Perception and action, on the other hand, are subsymbolic and better described in the analogic realm of dynamics. Yet the fact that gesture shares a semantic and communicative burden with speech as well as a tight temporal coupling means that they must also share a common, integrative mechanism. Indeed our speculative model offers a mechanism — dynamics — by which these seemingly incommensurate codes may be reconciled. We suggest that just as these aspects are linked initially, when language emerges, so they remain coupled throughout life.[1]

The issue of commensurate codes is equally relevant for all aspects of human cognition. Cognition — remembering, planning, deciding, and rehearsing — is abstract and mental and often couched in terms of concepts and symbols. Again, perception and action deals with the here-and-now and seems not to require an elaborate representational structure. But if we consider how real people behave in everyday life, it is impossible to draw a line between the two modes of processing. Sometimes people engage in contemplation, problem solving, and day-dreaming, where mental activity is predominant. At other times, the situation demands being closely ‘clamped’ to the

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[1] For a recent review of dynamic approaches in cognitive science, see Beer (in press). Efforts to cast mental events in the language of dynamics or connectionist networks have increased in the last decade. See, for instance, Elman’s (1995) work on connectionist models of language, Thelen *et al*. (in press) for a dynamic model of Piaget’s A-not-B error, and Schöner *et al*. (1995) and Pfeiffer and Scheier (1999) for work in autonomous robots.

environment (Glenberg, 1997). But most often, people shift rapidly and seamlessly between the two types of engagement: having moments of thought interspersed with nearly continual on-line activity. For instance, imagine driving down the highway mentally reviewing your next lecture when a deer darts in front of the car. In a split second, you become totally and completely 'clamped' to the immediate situation. Or consider the ability to mentally rehearse an unfamiliar route or a difficult and new motor skill and then carry it out (Jeannerod, 1997). Here again, it is difficult to imagine how this integration of thought and perception–action could be accomplished if their mental currencies are fundamentally incompatible. The issue, therefore, is not how to transgress a divide between cognition and action or between body and mind. The integration is seamless in both directions. Rather, the critical dimension is the balance between on- and off-line, or the relative strength of the coupling between the mental dynamics and those of the body and the environment. Put another way, people are adept at shifting the relative dominance of the immediate input versus the relative strength of the remembered input as the context demands.

This formulation also recasts the developmental issue. Traditionally, cognitive development is construed as moving from purely sensorimotor processing to that which is more conceptual and abstract. Gaining the ability to process 'off-line' is indeed a tremendous developmental advance, moving infants from being dominated by the immediate input to the ability to hold aspects of the environment in memory and using those stored memories to plan actions. But children must also learn to perform well on-line and, most importantly, to rapidly and appropriately switch between these modes of functioning. In terms of a dynamic model, this means tight coupling when the occasion warrants, but also great flexibility to modulate that coupling when the situation demands different skills. Thus, development is not so much saying 'bye-bye' to being in the world as learning to use cumulative experiences to adaptively act in the world.

In sum, our argument for embodiment rests on the necessity for compatible dynamics so that perception, action, and cognition can be mutually and flexibly coupled. Such dynamic mutuality means that activity in any component of the system can potentially entrain activity in any other component, as illustrated by von Holst's principles. We suggested that in the development of communication, rhythmic manual activity captured and entrained the coordination of the oral system and that both were linked with emerging speech and language. In that all cognition grows from perception and action and remains tied to it, body, world and mind are always united by these common dynamics. Action influences thought as much as thought motivates action.

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