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Gesture Gives a Hand to Language and Learning: Perspectives from Cognitive Neuroscience, Developmental Psychology and Education

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Abstract

People of all ages, cultures and backgrounds gesture when they speak. These hand movements are so natural and pervasive that researchers across many fields – from linguistics to psychology to neuroscience – have claimed that the two modalities form an integrated system of meaning during language production and comprehension. This special relationship has implications for a variety of research and applied domains. Gestures may provide unique insights into language and cognitive development, and also help clinicians identify, understand and even treat developmental disorders in childhood. In addition, research in education suggests that teachers can use gesture to become even more effective in several fundamental aspects of their profession, including communication, assessment of student knowledge, and the ability to instill a profound understanding of abstract concepts in traditionally difficult domains such as language and mathematics. This work converging from multiple perspectives will push researchers and practitioners alike to view hand gestures in a new and constructive way.

Hand gestures are a natural, ubiquitous and meaningful part of spoken language – so much so, researchers have claimed that gesture and speech form a tightly integrated system during language production and comprehension (McNeill 1992, 2005; Clark 1996; Goldin-Meadow 2003; Kita and Özyürek 2003; Kendon 2004; Özyürek and Kelly 2007). David McNeill, focusing on language production, was the first to argue that gesture and speech make up a single, integrated system of meaning expression (1992). He posited that because gesture and speech temporally overlap but convey information in two very different ways – speech is conventionalized and arbitrary, whereas gesture is idiosyncratic and imagistic – the two modalities capture and reflect different aspects of a unitary underlying cognitive process. Thus, according to McNeill, gesture and speech combine to reveal meaning that is not fully captured in one modality alone. For example, imagine explaining to a child how to tie a shoe without actually physically touching the laces. It is surprisingly hard to

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explain this simple and common action without moving one's hands (try it), but adding gesture to speech makes it very easy and understandable.

There are four main types of co-speech gesture (McNeill 1992). The above example illustrates an iconic gesture – these are gestures that imagistically represent object attributes, actions and spatial relationships. A second type of gesture is a deictic, or pointing, gesture. These gestures index, or connect, some aspect of speech to some other idea, object, location or action. For example, imagine you are hiking through dense vegetation and your more experienced travel companion says, 'Watch out for that poison ivy'. Without a deictic gesture to the plant, you might be in for a long and unpleasant camping trip! A third type of gesture is a metaphoric, which conveys an abstract idea in a concrete form. For example, during a brainstorming session on a new advertising campaign, a marketing executive may say, 'Here's what I am thinking', while holding her fingers at her forehead and temples, and then suddenly thrusting them outward as if holding an object out to the group. This is metaphoric because it is impossible to physically remove an idea from one's head and literally present it to others, but the gesture in this case conveys that meaning nonetheless. Finally, beat gestures are hand movements that keep the rhythm of speech. These gestures are not thought to convey any semantic content, but they do connect portions of discourse over large spans. For example, if a chef were to explain the sequence of adding ingredients to a stir-fry, he might say, 'You add the lemongrass, the ginger and then the basil' while making beat gestures (right hand repeatedly flipping outward every time he mentioned an ingredient) throughout the sequence to create a sense of rhythm and cohesive structure. These four types of gestures are different from a fifth prominent gesture called an emblem. Emblems, such as the 'thumbs up' or 'peace sign', are hand configurations that have a culturally specified meaning, and unlike co-speech gesture, they convey information independently of speech. In fact, emblems often stand alone from speech – think of how you might communicate with only a gesture (and there is a range of options here) to an aggressive driver who just cut you off!

There are two elements of the speech–gesture relationship that are particularly interesting and require further explanation. A crucial aspect of co-speech gestures is the tight temporal synchrony with the accompanying speech. According to McNeill (1992), co-speech gestures do not make sense without the accompanying speech, and so it is very important to study gestures in the context of the accompanying speech – that is, to study them as a combined system, not as two separate things. Related to this, the second key feature is that gesture and speech combine to reveal meaning that goes beyond the sum of the two individual parts. Consider an example. Suppose a friend describes to you how he got into an auto accident by saying, 'I didn't see it coming'. In gesture, your friend might represent how the cars collided by making two, perpendicular flat-handed

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gestures that move toward one another (making a T shape). The addition of this iconic gesture would provide a much clearer and more elaborate representation of what happened: the reason your friend 'didn't see it coming' was that the other car blindsided him from the passenger side. In this way, the simultaneous coupling of gesture and speech conveys information that is much more complete than the information conveyed through speech or gesture alone.

The present review adopts the theoretical stance put forth by McNeill and others that gesture and speech indeed do comprise an integrated system. Although historically there has been some debate about the issue – see Krauss 1998, and Krauss et al. 1991, for the view that gesture and speech are two separate systems,[1] and that gesture plays a role merely in accessing words during language production – the majority of recent research on the topic supports the integrated system account of gesture and speech during language production and comprehension.

Specifically, the present review adopts an evolutionary and embodied perspective on the relationship between the two modalities in language use (for a more detailed account of this theoretical perspective, see Kelly et al. 2002a). Researchers have argued that human language has evolved from nonverbal communication systems in our evolutionary past (Rizzolatti and Arbib 1998; Armstrong 1999; Bates and Dick 2002; Corballis 2003). Although it is very difficult to prove this claim with archeological fossil records, the present review assumes that we may gain insights into this integrated relationship by focusing on present-day *behavioral and neurocognitive fossils* (Povinelli 1993). That is, if spoken language systems emerged from gestural communication systems in our evolutionary past, one would hypothesize that this integrated relationship is carried through and maintained in present-day language use and development. And if spoken language is grounded in nonverbal communication systems, it suggests that the neural mechanisms connecting gesture and speech may not be solely linguistic in nature, but imagistic, motoric, and even emotional as well.

So what is the empirical evidence to support this integrated view? We begin by covering recent research in cognitive neuroscience that explores the neural mechanisms for gesture–speech processing. We then examine the role that gesture plays with speech in typically and atypically developing children. Next, we highlight the importance of considering gesture in the context of teaching and learning. Finally, we finish by outlining some future directions in studying the integrated nature of gesture and speech in communication.

The Cognitive Neuroscience of Gesture

It is now well established in behavioral studies in psychology that gesture and speech have an integrated relationship in language production (Alibali

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et al. 2000; Goldin-Meadow 2003; Kita and Özyürek 2003) and language comprehension (Goldin-Meadow et al. 1992; Kelly and Church 1997, 1998; Beattie and Shovelton 1999; Cassell et al. 1999; Kelly et al. 1999). To grossly sum up, these studies have shown that producing and comprehending speech is significantly influenced by the presence of co-speech gestures. However, it is difficult to determine from this research the extent of this integrated relationship – that is, are speech and gesture also linked at a level beneath the overt behavior? Recently, researchers in the field of cognitive neuroscience have addressed this question by investigating the neural mechanisms that underlie cognitive and social processes and behaviors. This line of work is very informative because it highlights neural processes and structures that reveal *why* gesture and speech form an integrated system on the psychological and social levels of analysis. Understanding the relationship between gesture and speech on multiple levels allows for more robust claims about this integrated system.

A glimpse of the neural relationship between speech and gesture was first seen with the discovery of 'mirror neurons' in area F5 of monkeys, the rostral part of the ventral premotor cortex and purported homologue to Broca's area (an important language region in the left hemisphere) in the human brain (di Pellegrino et al. 1992; Gallese et al. 1996; Rizzolatti and Arbib 1998). These neurons discharge when a monkey both executes a specific manual action and when he observes another primate executing the same action. Since their discovery, several papers have demonstrated that the human brain, specifically Broca's area, also has similar 'mirror properties' (for a review, see Nishitani et al. 2005). This suggests a link between neural areas responsible for hand actions and language.

This linkage between language and action areas of the brain has been fleshed out by a number of recent experiments with humans using different types of cognitive neuroscience methods (for a nice recent review, see Willems and Hagoort 2007). Indeed, several studies have found that brain regions that process speech also process actions made with the hand (Bonda et al. 1996; Puce and Perrett 2003; Gallese et al. 2004; Nishitani et al. 2005). For example, the superior temporal region (STS) in the left hemisphere is implicated not only in processing sound-based representations of speech (Hickok and Poeppel 2000) but also goal-directed hand movements (Bonda et al. 1996). In addition, evidence from research using transcranial magnetic stimulation (which interferes with or enhances the neural processing of stimuli) demonstrates that when there are disruptions to parts of the brain that control hand movements, speech comprehension also suffers (Flöel et al. 2003).

In another suggestive line of work, researchers have demonstrated that the neural processing of action verbs is somatotopically organized in the premotor and motor cortices (Pulvermuller et al. 2005; Tettamanti et al. 2005). For example, Tettamanti et al. (2005) used functional magnetic resonance imaging (fMRI, which measures blood flow in the brain in

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response to stimuli) to investigate the neural processing of sentences containing verbs using different body parts (e.g. 'catch' vs. 'kick'). They found that sentences with the different verbs activated corresponding parts of the premotor cortex (a part of the mirror neuron system in humans); that is, 'catch' activated hand areas and 'kick' activated foot areas. As a test of whether this neural activation plays a functional role in action verb processing, Pulvermuller et al. (2005) applied transcranial magnetic stimulation (in this case, enhancing neural processing) while participants listened to different types of actions words. They found that stimulating hand regions sped reaction times to hand words but not foot words and stimulating foot regions sped reaction times to foot words but not hands words. This is strong evidence that activating brain areas involved in action execution plays a *causal* role in comprehending (and perhaps producing) language about actions, and provides suggestive evidence that communicative hand movements, such as gesture, may share a special link with speech during language use.

Indeed, very recent work has begun to flesh out this neural link. Montgomery et al. (2007), using fMRI,[2] found that the inferior parietal lobule, another area purported to be part of the human mirror neuron system, was equally active when adults viewed, imitated and produced communicative hand gestures (emblems such as the 'thumbs up' gesture) and actions towards objects (iconic gestures such as pounding a nail). This similar activation suggests that the human mirror neuron system may be involved in producing and comprehending hand gestures in the absence of speech.

Focusing on gestures that do accompany speech, researchers have started to identify mechanisms for how the two modalities may be integrated in the brain (Hubbard et al. 2007; Skipper et al. 2007; Willems et al. 2007; Holle et al. 2008; Wilson et al. 2008). For example, Willems et al. (2007) used fMRI to show that Broca's area integrates gestural and spoken information in a similar fashion during sentence comprehension, suggesting a common neural mechanism for processing the two types of communication. In addition, Skipper et al. (2007) used fMRI to show that Broca's area may be partly responsible for integrating gesture and speech. Specifically, they had participants watch videos of different stories comprised of speech and gesture and found that connections among Broca's area and other cortical areas (e.g. motor areas involved in gesture processing) were weaker for stories containing congruent speech and gesture compared to stories containing irrelevant self-grooming movements. This weaker connection, according to the authors, reflected gesture's ability to reduce the workload of Broca's area in processing the meaning of the accompanying speech. Moreover, recent research has shown that in addition to traditional language areas, other brain regions may be recruited for comprehending verbal and gestural utterances, such as multimodal integration sites (STS), other parts of the mirror neuron system (inferior parietal lobule and

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premotor regions) and emotional centers such as the cingulate cortex (Calvert and Thesen 2004; Holle et al. 2008; Wilson et al. 2008). These new findings suggest that gestures may interact with speech not just in a linguistic way, but imagistic, motoric and affective fashions as well.

As a different test of whether gesture and speech form an integrated system, researchers have used event-related potentials (ERPs, measuring the brain's electrical response to stimuli) to explore the online processing (i.e. the immediate integration) of gesture and speech during language comprehension (Kelly et al. 2004, 2007; Holle and Gunter 2007; Özyürek et al. 2007; Wu and Coulson 2007a,b). For example, Wu and Coulson (2007b) presented gesture–speech utterances followed by pictures that were either related to gesture and speech or just the speech alone. When pictures were related to gesture and speech, participants produced a smaller N400 effect (the traditional semantic integration effect that occurs 400 ms after stimulus onset; see Kutas and Hillyard 1980) and N300 effect (image-based semantic integration that occurs 300 ms after stimulus onset; see McPherson and Holcomb 1999) than when the pictures were related to just the speech. Because small N300 and N400 effects typically reflect ease of integrating linguistic information, this finding suggests that visuo-spatial aspects of gestures facilitated subsequent processing of the speech. In this way, gesture may have combined with speech to build stronger and more vivid expectations of the pictures than just speech alone.

Researchers have also demonstrated that the semantic content of gesture influences the processing of accompanying speech. For example, Kelly et al. (2004) presented gesture–speech pairs that were congruent (saying tall while gesturing the 'tallness' of a tall container) versus incongruent (saying tall while gesturing the 'shortness' of a short container), and found that incongruent gestures produced a larger N400 effect to speech than congruent gestures. More recently, Özyürek et al. (2007) demonstrated that the semantic content of gesture and speech are processed similarly (i.e. identical N400s to words and gestures that were incongruent with a previous sentence context), providing a nice complement to their fMRI work (Willems et al. 2007) demonstrating a shared mechanism for the semantic processing of the two modalities in the brain. Moreover, the semantic integration of gesture and speech is affected by contextual factors (Holle and Gunter 2007; Kelly et al. 2007). For example, Holle and Gunter (2007) showed that the presence of non-meaningful gestures (e.g. grooming behaviors) influences the extent to which meaningful gestures are integrated with speech – that is, the presence of non-meaningful gestures reduces the size of the N400 effect to incongruent meaningful gestures – during sentence processing. This effect of context is exciting because it suggests that the integration of gesture and speech may not be an entirely automatic and obligatory neurocognitive process.

Together, these studies from the field of cognitive neuroscience complement the work from psychology – gesture influences the behavioral

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processing of speech during language production and comprehension, and one explanation for this behavioral finding is that gesture and speech are integrated in space and time in the brain's processing of this information. We next turn to the implications of this neural relationship in the domain of language and cognitive development.

Gesture and Development

Another way to explore the relationship between gesture and speech is to study children. Indeed, researchers have theorized that if gesture and speech form an integrated system, gestures should play an important role in language and cognitive development (Bates and Dick 2002; Kelly et al. 2002a).

Deictic and iconic gestures are pervasive in children's speech. Children produce deictic gestures before they begin to talk (Bates 1976; Butcher and Goldin-Meadow 2000), and shortly thereafter (usually by 18 months), they produce iconic gestures along with their speech (Bates et al. 1979; Masur 1983; Morford and Goldin-Meadow 1992; Iverson et al. 1994; Butcher and Goldin-Meadow 2000). Throughout childhood, deictic and iconic gestures become more complex and frequent (Jancovic et al. 1975; McNeill 1992), and children produce them in a number of different contexts: with friends (Azmitia and Perlmutter 1989; Church and Ayman-Nolley 1995), family (Bates 1976), and teachers (Fernandez et al. 1996). They also use gestures while talking about a number of different topics: telling stories (McNeill 1992), giving directions (Iverson and Goldin-Meadow 1997), and explaining concepts (Church and Goldin-Meadow 1986; Perry et al. 1988, 1992).

Several studies suggest that the gestures children produce while speaking reveal much more about what they are thinking than does their speech alone (Church and Goldin-Meadow 1986; Perry et al. 1988; 1992; Alibali and Goldin-Meadow 1993; Goldin-Meadow et al. 1993; Church et al. 1995; Garber 1997; Alibali 1999; Church 1999; Goldin-Meadow 2000). For example, in a study investigating the role of gesture in children's explanations of Piagetian (1967) conservation problems, Church and Goldin-Meadow (1986) discovered that children frequently produced iconic gestures in their explanations and that those gestures conveyed different information than the spoken component of the explanations (gesture–speech mismatches). For example, one child explained that two containers of water (a tall, thin glass and a short, wide dish) were different because, 'One was short and one was tall', while simultaneously gesturing that the two containers had different widths. This suggests that the child knew more about the problem than his speech let on. The 'mismatch' phenomenon generalizes to more traditional educational domains as well, such as mathematics. For example, Perry et al. (1988, 1992) found that when 10-year-old children solve math problems (e.g. 3 + 4 + 5 = __ + 5), their deictic gestures often reflect different strategies than does their speech.

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For example, a child producing 'speech–gesture mismatch' might say that he added up all the numbers on the left side to get his answer, but he may simultaneously point to *all* of the numbers in the equation, including '5' on the right-hand side of the problem.

One of the most interesting findings in these studies (Church and Goldin-Meadow 1986; Perry et al. 1988) was that the children who produced many gesture–speech mismatches in their explanations were precisely the ones who later benefited most from instruction on those problems. This finding suggests that speech and gesture can serve as an index of transitional, implicit knowledge in a specific domain and may be a way of determining a child's 'readiness to learn'. The claim that gestures reflect implicit knowledge and readiness to learn fits nicely with educational research arguing that teachers can better interpret a student's work by being aware of that student's underlying or implicit understanding of a topic (Ball 1993; Carpenter et al. 1996, 1998). For example, Carpenter et al. (1996) argued that awareness of children's implicit understanding of mathematical concepts could allow teachers to better assess and instruct children in that domain. If hand gestures are a window into this implicit knowledge, attention to this information may make this task easier. We will return to the educational implications of gesture in a later session.

Gesture and Atypical Development

Researchers have also investigated the role of gesture in atypical development. With regard to language production, one interesting finding is that congenitally blind children gesture when they speak (Iverson and Goldin-Meadow 1998). Moreover, these children gesture even when speaking to other blind children. The fact that language learners produce gestures without ever having seen them is some of the best evidence that speech and gesture form a tightly integrated system indeed.

This integrated relationship can also be seen in children with developmental delays and disorders. For example, deficits in gesture production positively correlate with deficits in cognition and language (Thal and Bates 1988; Thal et al. 1999; Charman et al. 2003). Charman et al. (2003) found that preschool-aged children with autism spectrum disorder, a disorder that compromises communication and social cognition, were delayed compared to typically developing children in their ability to produce deictic gestures that involved shared reference (e.g. pointing to an object that can be seen by two people). Moreover, research focusing on children with Specific Language Impairment (SLI), a disorder that causes delays in language but generally spares other cognitive abilities, has also uncovered gesture production deficits. Toddlers with SLI, or who are at risk of SLI, demonstrate deficits in their ability to produce and imitate symbolic gestures (e.g. flapping hands to represent a birds) compared to typically developing peers (Thal and Bates 1988; Thal et al. 1999).

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Although gesture is often impaired in children with developmental delays and disorders, there is evidence that gestures may at times compensate for cognitive and language deficits as well (Harris et al. 1997; Iverson et al. 2003; Stefanini et al. 2007). For example, children with Down syndrome produce more gestures than children with Williams syndrome (Harris et al. 1997) and also typically developing children (Caselli et al. 1998). This finding suggests that Down syndrome children, more than Williams syndrome and typically developing children, may use hand gestures to 'make up' for language problems (Stefanini et al. 2007; but see Iverson et al. 2003 for a different view). The compensatory use of gesture apparently also occurs in children with SLI. For example, Evans et al. (2001) found that children with SLI often presented information uniquely in their gesture compared to their speech. Moreover, this gestural information was often more sophisticated than their speech. The authors concluded that because SLI children have phonological deficits in their speech, gesture allows them to reveal knowledge in an embodied format that is easier for them to express, and in this way, they may be able to overcome their linguistic difficulties by simply moving their hands.

Gesture may also be used to predict developmental delays (Mundy et al. 1995; Brady et al. 2004; Mitchell et al. 2006; Luyster et al. 2007; Smith et al. 2007). Brady et al. (2004) found that the children with general developmental delays who produced pointing gestures showed greater increase in expressive language abilities than children who did not point. This suggests that deictic gestures may be indicative of future language growth in developmentally delayed children. Gestures are also useful for predicting language outcomes in children with autism. For instance, Smith et al. (2007) discovered that in children with autism, the number of gestures used to initiate joint attention – the ability to direct and share attention with another – was linked to greater vocabulary growth after two years of intervention. Moreover, Mitchell et al. (2006) demonstrated that gestures might be better than speech in the early identification of the disorder. Using the MacArthur Communicative Development Inventory, the researchers found that the gestural repertoires (e.g. the production of deictic and emblematic gestures) of 12-month-old infants differentiated children who were and were not later diagnosed with autism spectrum disorder at 24 months of age. Impressively, these gestural indicators were evident a full 6 months before any verbal patterns differentiated the two groups of children.

If gestures are helpful in early identification of developmental disorders, they may be useful in early interventions as well (McCathren 2000; Whittaker and Reynolds 2000; Yoder and Warren 2001a,b; Calculator 2002; Brady et al. 2004). Brady et al. (2004) found that high parental responsiveness to the gestures of children with language delays predicted higher expressive and receptive language scores in those children. Given the positive effects of parental responsiveness, it makes sense to explicitly instruct parents

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to attend to gesture. Indeed, Calculator (2002) trained parents of children with Angelman syndrome – a disorder involving disfluent speech and general motor deficits – to recognize enhanced natural gestures, which are intentional behaviors in a child's motor repertoire (e.g. teaching the child to use a 'drink' gesture to request a glass of milk). Parents reported that this training greatly helped them recognize more of their children's gestures and communicative attempts. With regard to parental gestures, McCathren (2000) showed that training parents to imitate certain hand and body gestures of developmentally delayed children was effective at enhancing intentional communication between parent and child.

Another approach is to train developmentally delayed children to compensate for delays by using their own gestures more effectively (Buffington et al. 1998; McCathren 2000; Whittaker and Reynolds 2000; Yoder and Warren 2001b; Calculator 2002). Buffington et al. (1998) attempted to teach autistic children appropriate gestural responses to stimuli. As a pretest, they presented verbal and nonverbal stimuli to children and observed their gestural and verbal responses. Then there was a gestural training phase that included physically modeling, prompting, and reinforcing correct responses. After training, the researchers found that the children increased their appropriate gestural responses to novel stimuli as they progressed through treatment. The authors concluded that if children with autism can learn early on to produce socially appropriate gestures, they may have more successful social interactions later in life.

It is important to note that many of the gestures identified in this section are different from the standard 'co-speech' gestures discussed in this paper. Indeed, the majority of gestures in the above studies are emblematic or deictic gestures that occur in isolation from speech. Given the importance of understanding the relationship between speech and gesture, an exciting direction for future research is to focus on the combination of the two modalities in order to provide an additional layer of clinical insight into the various linguistic, cognitive and social disorders that develop in childhood.

Gesture and Education

Even a casual observation of teachers and students interacting in the classroom will reveal that gestures are as pervasive as blackboards, desks and lesson plans. Because gesture is so prevalent in this environment, it is important to consider what role these hand movements play in educational situations involving teaching and learning.

One powerful role is that gesture production may help children (and adults) free up cognitive capacity when communicating about conceptual problems (Goldin-Meadow et al. 2001; Cook and Goldin-Meadow 2006). For example, Goldin-Meadow et al. (2001) had 10-year-old children and adults explain their understanding of difficult math problems (e.g. $3 + 4 + 5 = \_\_ + 5$ for children; $X + 2X + X/2 = 21$ for adults) with and

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without deictic gestures. Simultaneously, they were asked to perform a cognitive load task requiring them to remember short lists of words. The main finding was that participants remembered the most words when they gestured than when they did not gesture. This effect generalized even when the cognitive load was more spatial in nature, but the effect disappeared when the semantic content of the gesture was not congruent with the accompanying speech (Wagner et al. 2004). In addition, children who produce gestures in these sorts of math problems are more likely to sustain learning over long periods of time (Cook et al. 2008). Finally, explicitly requiring children to move their hands while explaining their (incorrect) understanding of these types of math problems causes them to produce new strategies in gesture not previously conveyed in their speech, and makes them more receptive to subsequent instruction on how to correctly solve the problems (Broaders et al. 2007).

Gestures also influence how information is exchanged between teachers and students during learning sessions. For example, Goldin-Meadow and Sandhofer (1999) observed natural adult–child interactions and discovered that adults often incorporated children's deictic and iconic gestures into what they thought that children had verbally explained (about Piagetian conservation problems) in their speech. This has obvious educational implications. For example, if a child verbally described the different heights of two objects but gesturally represented the different widths, adults may make an assessment of that child's knowledge that incorporates height *and* width. This sensitivity to gesture is, not surprisingly, evident in teachers as well. Alibali et al. (1997) demonstrated that teachers often incorporate gestured information into their assessments of children's knowledge of mathematical equivalence (i.e. problems of this form, $3 + 4 + 5 = \_\_ + 5$). For example, if a child points to a number that he did not mention in his speech, teachers often incorporate that gestured number into an assessment of what that child knows about the problem. However, there is room for improvement. Kelly et al. (2002b) found that training adults to pay attention to gesture helped them to better make assessments of children's knowledge of mathematical problems. For example, if regular adults – not teachers – are given a 5-minute instructional session on how children's gestures can add to speech, and are then shown videos of children producing mismatches (e.g. a child saying that he added up numbers only on the left, but pointing to *all* numbers in a problem), the adults incorporate gesture into their assessments of the children's knowledge more than adults without training.

Children are also sensitive to gesture in contexts of mathematical reasoning and learning (Kelly and Church 1997, 1998; Church et al. 2001). For example, Church et al. found that 10-year-old children showed a better understanding of mathematical concepts when nonverbal gestures accompanied verbal instruction on the concepts. This effect generalizes from the laboratory to actual educational interactions between children and teachers: Singer and Goldin-Meadow (2005) found that when teachers use

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gestures during math instruction, 10-year-old children learn the concepts better than when teachers use speech alone.

Given that gestures play a role in teaching and learning, teachers should be able to take advantage of gesture – their own and children's gestures – in the classroom. For example, Pozzer-Ardenghi and Roth (2007) have recently studied teacher–student interactions during high school biology lessons and found that for many concepts, hand gestures provided additional clarifying input for students. They reasoned that hand gestures and other visual aids might help students who are struggling with advanced concepts that are not easily represented and taught through speech alone. Indeed, when teaching first-grade children about basic mathematical concepts (i.e. counting numbers of objects), teachers frequently use nonverbal behaviors such as pointing, counting on fingers, circling objects with the finger, etc. (Flevares and Perry 2001). Interestingly, this visual clarification occurs more frequently when students appear confused. Moreover, this increased visual instruction often occurs in the absence of increased verbal clarification. In other words, teachers specifically use things like gestures to target students who struggle with mathematical concepts.

Teachers can also use gestures to help struggling learners in other domains as well. For example, when second language learners grapple with aspects of a new language, teachers can use gesture to help with these problems. In fact, in a recent literature review on the role of gesture in second language learning, Gullberg (2006) outlined several reasons why hand gestures may be a crucial tool in helping struggling learners master a new language. For example, she argues that visually rich gestures, such as iconic gestures, serve as ideal input to beginning learners of a second language. Although researchers have long claimed that teachers' gestures enhance second language instruction for learners (Moskowitz 1976), there is a surprising paucity of experimental work investigating this issue (but see Allen 1995; Sueyoshi and Hardison 2005). In one recent study on this topic, Kelly et al. (2007) found that iconic gestures helped English-speaking adults to learn and remember novel Japanese words. For example, producing a drink gesture while saying, 'Nomu means drink', helped people remember the meaning of the Japanese word. Interestingly, the gestures did not help simply because they captured visual attention – in fact, the gestures facilitated learning only when they conveyed congruent information to speech, but they disrupted learning when they conveyed incongruent information. So gesture does not promote learning merely because of hand waving – content matters.

In perhaps the most extreme demonstration that gestures help confused learners in second language contexts, Church et al. (2004) studied how gestures aid first-grade Spanish speakers (with English as a second language) learn novel mathematical concepts (like the Piagetian conservation problems described above) in their second language. The children – who did not speak *any* English – were shown instructional videos in English

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that contained or did not contain gesture. Remarkably, the children improved twice as much in their understanding of the mathematical concepts when verbal instruction included gesture. The authors argued that although the Spanish speakers did not understand the verbal portion of the training, the gesture represented universal aspects of the mathematical concepts, and these aspects are accessible even when someone does not speak a language.

Future Directions

Although there has been a flurry of research on gesture within the last decade, there are many avenues yet to be explored. In addition to delving deeper within disciplines, there are new and stimulating opportunities to make connections between research areas. One exciting direction is to bring cognitive neuroscience techniques into traditional developmental, clinical and educational domains. For example, Sheehan et al. (2007) have recently completed the first developmental study to investigate the neural processing of gesture and speech in young children. Using ERPs, they found that speech and gesture appear to share a similar neural system in early stages of language acquisition (18 months), but the two systems began to diverge shortly thereafter at 2 years of age. Given what we know about the integrated neural relationship of gesture and speech in adults, it would be interesting to explore when and how the two systems come back together at later stages of development.

Connecting to clinical psychology, cognitive neuroscientists have recently advanced theories that autism may be a disorder caused by a breakdown in the mirror neuron system (Williams et al. 2001), and new research has just recently started to use fMRI to investigate neural correlates of autistic children's inability to successfully imitate nonverbal behaviors (Dapretto et al. 2006). In the work by Dapretto et al., the researchers showed that the higher an autistic children's score on a test that involved imitating faces, the more their inferior frontal gyrus was active. Because the inferior frontal gyrus is also implicated in the integration of hand gesture and speech (Skipper et al. 2007; Willems et al. 2007), it would be interesting to extend this research with autistic children into the realm of imitating language and hand gestures.

With regard to education, researchers are just beginning to explore the neural role that gesture plays when people master and retain new information in learning/teaching contexts. For example, Kelly et al. (2007) recently used ERPs to investigate whether gestures play a role in second language learning. In an experiment that taught adults novel Japanese verbs with and without iconic hand gestures, they demonstrated that words learned with gesture produced deeper and stronger neural memory traces, as measured by the Late Positive Complex, which indexes strength of memory encoding (Rugg and Curran 2007). This is an exciting development, because it

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suggests that gesture and speech not only have an integrated neural relationship during language comprehension, but this relationship may be preserved in lasting memories formed as a product of learning.

Another interesting direction in gesture research connects to a very different domain – computer science. With people increasingly interacting with computing technologies, computer scientists have recognized the importance of creating more life-like 'embodied conversational agents' that serve as the interface between humans and machines (Wachsmuth 2002; Kopp and Wachsmuth 2004; Cassell 2007; Cassell et al. 2007). This work has demonstrated how the integrated systems view of gesture and speech has helped programmers design more natural conversational agents – indeed, people like interacting with gesturing conversational agents better than non-gesturing ones (Cassell et al. 2001). On the flip side, computer models and simulations have in turn informed theories of gesture and speech. For example, Cassell et al. (2007) has recently created an embodied conversational agent that spontaneously produces novel gestures along with speech, providing a computational model of how the form of gesture and the content of speech interface to capture a common representation and pragmatic function. This sort of research is interesting because it represents early steps to computationally test theories of how gesture and speech interact in real human face-to-face communication.

In addition to these varied avenues for future research, there still remain a number of other important research questions. For example, to what extent are hand gestures processed similarly or differently than other actions made with the hand (e.g. reaching behaviors, physical manipulations of objects, pantomimes, etc.)? How are gestures different in one's native language compared to a second (or third, or fourth . . .) language? Are there different neural mechanisms involved in gesture production compared to gesture comprehension? Finally, now that the evidence strongly favors the view that gesture and speech are indeed an integrated system, what exactly is the nature of this system: is it propositional, imagistic, spatial, motoric, or some combination of these?

Answering questions such as these should keep gesture research active for years to come.

Conclusion

People gesture when they speak. Research across multiple disciplines – from linguistics to psychology to neuroscience – supports the theoretical claim that these gestures have a special connection to the words they accompany. Understanding this integrated relationship provides useful insights into how children and adults comprehend language, how they allocate resources while speaking, and how they think during problem solving. This knowledge may help clinicians and teachers to better identify and treat children with developmental disorders and to more successfully communicate with

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struggling learners. Moreover, researchers continue to advance new questions about gesture and speech that not only allow us to go deeper within traditional research domains, but help us make connections across disciplines as well. Ultimately, it is our hope that this growing focus on hand gestures will change the way we all view these curious hand movements that seem to be such a natural and ubiquitous part of human language.

Short Biography

Spencer D. Kelly received his PhD in developmental psychology from the University of Chicago and is currently an associate professor of psychology and neuroscience at Colgate University. His research focuses on the role that hand gestures play in language processing and development. He has published a number of papers on this topic (in *Brain and Language*, *Child Development*, *Developmental Neuropsychology*, and *Journal of Memory and Language*) and recently (2007) co-edited the first special issue on gesture, brain and language in the journal, *Brain and Language*.

Sarah Manning received a BA in mathematics and BFA in painting from Cornell University. A Fulbright Scholar, former mathematics teacher and technology executive in New York City, she is the President of Learnimation, an organization committed to improving mathematics education.

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Notes

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[1] Also see De Ruiter (2000) for a model that presents gesture and speech as both integrated and independent depending on different stages of language production.

[2] Refer to an earlier study by Gunter and Bach (2004) for an electrophysiological account of how the brain processes emblematic gestures in the absence of speech.

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