item length *Q. J. Exp. Psychol*. 44A, 47–67

57 Case, R.D., Kurland, M. and Goldberg, J. (1982) Operational efficiency and the growth of short-term memory span *J. Exp. Child Psychol*. 33, 386–404

58 Towse, J.N., Hitch, G. and Hutton, U. (1998) A re-evaluation of working memory capacity in children *J. Mem. Lang*. 39, 195–217

59 Swanson, H.L. (1999) What develops in working memory? A life span perspective *Dev. Psychol*. 35, 986–1000

60 Adams, J.W. and Hitch, G.J. (1997) Working memory and children's mental addition *J. Exp. Child Psychol*. 67, 21–38

61 Logie, R.H., Gilhooly, K.J. and Wynn, V. (1994) Counting on working memory in arithmetic problem solving *Mem. Cognit*. 22, 395–410

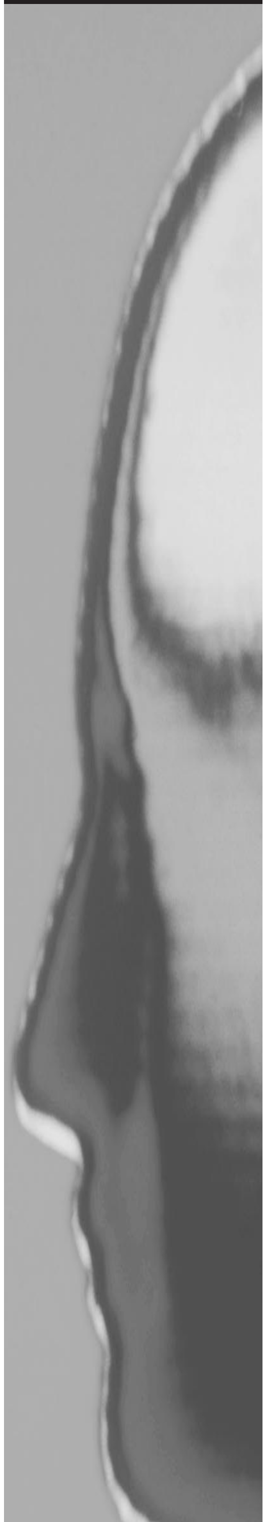
62 Bull, R. and Johnston, R.S. (1997) Children's arithmetic difficulties: contributions from processing speed, item identification, and short-term memory *J. Exp. Child Psychol*. 65, 1–24

63 Bull, R., Johnston, R.S. and Roy, J.A. (1999) Exploring the roles of the visuospatial sketchpad and central executive in children's arithmetical skills: views from cognition and developmental neuropsychology *Dev. Neuropsychol*. 15, 421–442

64 Leather, C.V. and Henry, L.A. (1994) Working memory span and phonological awareness tasks as a predictors of early reading ability *J. Exp. Child Psychol*. 58, 88–111

65 Daneman, M. and Green, I. (1986) Individual differences in comprehending and producing words in context *J. Mem. Lang*. 25, 1–18

66 Gathercole, S.E. and Pickering, S.J. Working memory deficits in children with special educational needs *Br. J. Spec. Educ*. (in press)



The role of gesture in communication and thinking

Susan Goldin-Meadow

People move their hands as they talk – they gesture. Gesturing is a robust phenomenon, found across cultures, ages, and tasks. Gesture is even found in individuals blind from birth. But what purpose, if any, does gesture serve? In this review, I begin by examining gesture when it stands on its own, substituting for speech and clearly serving a communicative function. When called upon to carry the full burden of communication, gesture assumes a language-like form, with structure at word and sentence levels. However, when produced along with speech, gesture assumes a different form – it becomes imagistic and analog. Despite its form, the gesture that accompanies speech also communicates. Trained coders can glean substantive information from gesture – information that is not always identical to that gleaned from speech. Gesture can thus serve as a research tool, shedding light on speakers' unspoken thoughts. The controversial question is whether gesture conveys information to listeners *not* trained to read them. Do spontaneous gestures communicate to ordinary listeners? Or might they be produced only for speakers themselves? I suggest these are not mutually exclusive functions – gesture serves as both a tool for communication for listeners, and a tool for thinking for speakers.

People gesture. This phenomenon has been remarked upon for at least 2000 years, across domains as diverse as philosophy, rhetoric, theater, divinity and language. The gestures that are most salient to speakers, and to listeners, are the codified (or conventionalized) forms that can substitute for speech. There is, however, another type of gesture that people routinely produce – informal, non-codified hand movements, fleetingly generated during the course of speaking. The content of these gestures is not typically the object of public scrutiny. As a result, these speech-accompanying gestures have the potential to reflect thoughts that may themselves be relatively unexamined by both speaker and listener. This type of gesture may thus reveal aspects of thought that are not seen in other, more codified forms of communication. In this review, I examine both types of gestures – those that substitute for speech, and those that accompany speech – with an eye towards understanding the role each plays in communication.

Gestures that substitute for speech

Gestures that have meaning independent of speech, and can occur on their own without speech, are known as 'emblems'[1]. Emblems have standards of form and can clearly be 'mispronounced'. For example, imagine producing the North American 'okay' gesture with the pinkie rather than the index finger touching the thumb – the resulting handshape is not recognizable as an 'okay'. For the most part, emblems are

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Box 1. Biological underpinnings of speech, sign and gesture

Sign languages can be characterized by the same kinds of organizational principles as spoken languages. There are, however, surface differences between the two types of languages, the most striking of which is that many linguistic devices in sign rely on spatial contrasts while speech is linear and non-spatial. In speakers, damage to the left hemisphere typically results in impairments in linguistic tasks, and damage to the right in impairments in spatial tasks. What happens then when signers, whose language is grounded in spatial contrasts, experience brain damage? It turns out that, like speakers, signers with left hemisphere lesions perform more poorly on language tasks than signers with right hemisphere lesions. Moreover, they do not show the deficits in spatial tasks that signers with right hemisphere lesions do. These findings suggest that sign is processed as linguistic information rather than spatial information, and that the left hemisphere is specialized for processing that information, be it transmitted by hand or mouth (Ref. a) (but see the recent discussion between Hickok, Bellugi and Klima, and Corina, Neville and Bavelier on the possibility that the right hemisphere also plays a role in sign language processing; Refs b,c).

The same question can be addressed in neurologically intact speakers and signers. Using behavioral tasks, Corina, Vaid and Bellugi (Ref. d) found left hemisphere specialization, not only when hearing speakers processed speech, but also when deaf signers processed sign. Interestingly, they found no evidence of hemispheric asymmetry when either group processed gesture – neither emblems (e.g. waving good-bye, giving the thumbs-up) nor sequences of limb movements that had no meaning. In addition to demonstrating once again the commonalties between sign and speech, this study underscores the differences between gestures that are organized around linguistic principles (e.g. ASL) and gestures that are not so organized.

Thus far, only emblems and nonmeaningful movements have been tested in these paradigms, leaving two interesting questions unanswered: (1) Do the non-codified and spontaneous gestures that accompany speech in hearing persons show left hemisphere dominance? The answer is likely to be 'no' as these gestures do not exhibit the hierarchically segmented structures found in spoken languages and codified sign languages. (2) Do the idiosyncratically codified gestures that deaf children of hearing parents create to serve the functions of a primary communication system show left hemisphere dominance? If truly linguistic, these home-made gesture systems are likely to be processed like natural language, signed or spoken, and thus are likely to be processed by the left hemisphere.

References

a Hickok, G., Bellugi, U. and Klima, E.S. (1996) The neurobiology of sign language and its implications for the neural basis of language *Nature* 381, 699–702

b Hickok, G., Bellugi, U. and Klima, E.S. (1998) What's right about the neural organization of sign language? A perspective on recent neuroimaging results *Trends Cognit. Sci.* 2, 465–468

c Corina, D.P., Neville, H.J. and Bavelier, D. (1998) Response *Trends Cognit. Sci* 2, 468–430

d Corina, D.P., Vaid, J. and Bellugi, U. (1992) The linguistic basis of left hemisphere specialization *Science* 255, 1258–1260

used to insult, praise or regulate the behavior of a communication partner[2]. Speakers who produce emblems are aware of having done so, and listeners are aware of having seen an emblem produced. In other words, emblems are consciously communicative.

Emblems are not, however, combined into gesture strings to make longer and more complex sentences – they do not form a linguistic system. The manual modality can, of course, support a system of gestures that has linguistic structure, as sign languages of the deaf illustrate. Sign languages, such as American Sign Language (ASL), are autonomous systems not based on the spoken languages of the hearing cultures that surround them[3–5]. Like spoken languages, sign languages are structured at syntactic[6,7] morphological[8,9] and phonological[10–12] levels and exhibit left hemisphere dominance (Box 1).

In addition to being primary communication systems, sign languages are also systems that have histories and are passed down from one generation of users to the next[13]. They are codified linguistic systems that assume the full burden of communication. There are, however, situations in which non-codified gesture is forced to take on the functions of a primary communication system; for example, deaf children whose hearing losses prevent them from acquiring spoken language even with intensive oral instruction, and whose hearing parents have not yet exposed them to sign language. Gesture is the primary means by which children in this situation communicate[14,15]. The question is whether their gestures assume the language-like forms characteristic of a codified communication system like ASL. The answer is that they do – on all levels that have been examined thus far.

Deaf children of hearing parents invent gestures that serve as the 'lexicon' of their communication system; the form of the gestures is stable over several years[16]. These lexical items are combined into gesture strings characterized by patterns reminiscent of ergative structures found in many natural languages (Box 2). In this sense, the gestures have syntactic structure. The systems also have morphological structure, with each gesture itself composed of smaller, meaningful handshape and motion components[17]. Finally, the gestures are language-like in that they are used for many of the functions of natural language – describing the non-present[18], 'talking' to oneself[19] and commenting metalinguistically on one's own or another's gestures[20].

The striking aspect of these gesture systems is that they are invented by deaf children who have access, not to conventional sign languages such as ASL, but only to the spontaneous gestures that their hearing parents use as they talk. While the deaf children's gesture systems have language-like structure, the hearing parents' gestures – like the gestures of all hearing speakers[21] – do not[22].

Is it possible to predict when the manual modality will assume language-like structure and when it will not? We[23] have suggested that the manual modality takes on grammatical properties *only* when it is required to carry the full burden of communication (as in conventional sign languages of the deaf, and unconventional gesture systems created by deaf children lacking language models). When the manual modality is used in conjunction with speech and does not carry the full burden of communication, it does not assume language-like form – that is, it does not convey meaning by rule-governed combinations of discrete units. Rather, these gestures convey meaning mimetically and idiosyncratically through continuously varying forms[21]. The question is whether the gestures that accompany speech play a role in communication despite the fact that they are not language-like in form.

Gestures that accompany speech

Nonverbal behaviors, including gestures that accompany speech, have traditionally been assumed to reflect speakers' feelings and emotions[24] and have been used by researchers as

Box 2. Spontaneous gesture systems created by deaf children

Unlike hearing children and adults who rarely concatenate their spontaneous gestures into strings (Refs a,b), deaf children who use gesture as their primary means of communication often convey their message via gesture sentences rather than single gestures. Deaf children of hearing parents in both American and Chinese cultures produce gesture sentences that conform closely to a structural analog of the ergative pattern predominating in some natural languages (Refs c,d); importantly though, neither English nor Mandarin (the grammatical structure noted in the deaf children's gesture systems is therefore not likely to have been derived from the structure of the spoken languages that surrounded them).

The hallmark of an ergative pattern is that the actor in an intransitive sentence ('you' in the proposition 'you move there') is treated differently (i.e. given a different syntactic or morphologic marking) from the actor in a transitive sentence ('you' in 'you eat pretzels'), and instead is marked like the patient ('pretzels'). By contrast, in an accusative language such as English, intransitive actors are treated like transitive actors and not like patients; for example, both actors precede the verb ('*you* move there' and '*you* eat pretzels') while patients follow the verb ('you eat *pretzels*').

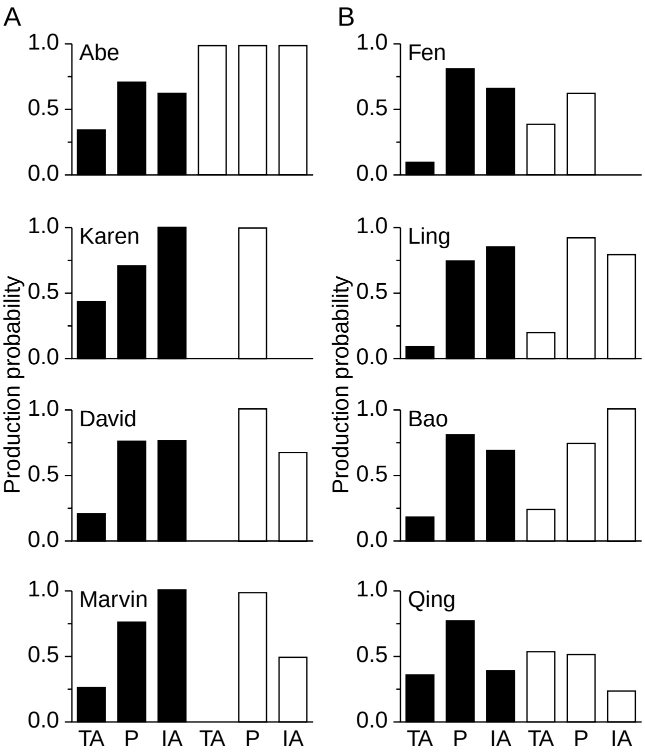

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Fig. I. Probability with which transitive actors (TA), patients (P), and intransitive actors (IA) are gestured. Probabilities were calculated using sentences in which three semantic elements could be gestured but only two elements actually were gestured. Both American (**A**) and Chinese (**B**) deaf children (dark bars, also identified by name) showed significant differences in production patterns across the three elements: gestures were produced reliably more often for intransitive actors than for transitive actors, but were equally likely for intransitive actors and patients – a structural analog of the ergative pattern found in certain natural languages. Hearing mothers (white bars) were not consistent in their treatment of intransitive actors, and thus did not display an ergative pattern. (Data redrawn from Ref. e.)

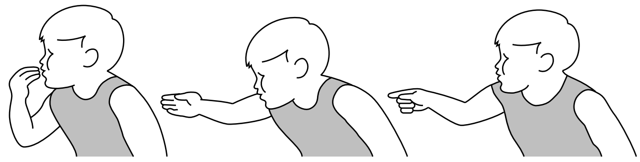

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Fig. II. A deaf child uses gesture to invite a listener to join him for pretzels. The child first indicates the action, 'eat', and then the actor, 'you' (the third gesture is a repetition of the second, presumably for emphasis). In this instance, the child omitted a gesture for the patient, the pretzels. Note that a typical pattern for English would be 'you eat' rather than 'eat you'.

The results of a study that examined how likely American and Chinese deaf children (and their hearing mothers) were to produce gestures for transitive actors, patients, and intransitive actors (Ref. e) are illustrated in Fig. I. In seven of the eight children, gestures were produced significantly more often for patients (pretzels) than for transitive actors (you, as eater). The crucial question is whether the deaf children treated intransitive actors (you, as mover) like patients or like transitive actors. In fact, gestures were produced significantly more often for intransitive actors than for transitive actors, and there were no significant differences between intransitive actors and patients. This production probability conformed to an ergative pattern – gesture production was equal for intransitive actors and patients, and distinct for transitive actors. Like their children, mothers tended to produce more gestures for patients than for transitive actors in the spontaneous gestures they produced when talking. However, unlike their children, they showed no reliable patterning of intransitive actors, and thus did not display an ergative pattern.

In addition to reliably producing some semantic elements at the expense of others, children were also consistent in where those elements were positioned in two-gesture strings. Intransitive actors were produced in the first position of a two-gesture string ('*you* move'), as were patients ('*pretzels* eat'). The one child who produced enough transitive actors for analysis showed an ergative pattern here too (Ref. f). He produced transitive actors in the second position of a two-gesture string ('eat *you*'; see Fig. II), thereby distinguishing this type of actor from both intransitive actors and patients.

The deaf children thus introduced into their gesture systems a pattern that can be found in natural languages, but that was not found in the spontaneous gestures their hearing parents used with them.

References

a Petitto, L.A. (1988) 'Language' in the prelinguistic child, in *The Development of Language and Language Researchers* (Kessel, F., ed.), pp. 187–221, Erlbaum

b McNeill, D. (1992) *Hand and Mind,* University of Chicago Press

c Dixon, R.M.W. (1994) *Ergativity*, Cambridge University Press

d Silverstein, M. (1976) Hierarchy of features and ergativity, in *Grammatical Categories in Australian Languages* (Dixon, R.M.W., ed.), pp. 112–171, Australian Institute of Aboriginal Studies

e Goldin-Meadow, S. and Mylander, C. (1998) Spontaneous sign systems created by deaf children in two cultures *Nature* 391, 279–281

f Goldin-Meadow, S. and Mylander, C. (1984) Gestural communication in deaf children: the effects and non-effects of parental input on early language development *Monogr. Soc. Res. Child Dev.* 49

a route to speakers' attitudes. But gesture has the potential to convey substantive information about a task (Box 3). Are researchers able to take advantage of this source of information into the speaker's thoughts?

The first step in addressing this question is to assess whether gesture can be interpreted reliably and consistently. A substantial number of investigators have observed the spontaneous gestures that accompany speech in conversations[25], narratives[21], descriptions of objects and actions[23], and explanations[26]. The gestures produced in these situations can be assigned meanings and, most importantly, independent observers reliably assign the same meaning to the same gesture.

The second step is to determine whether the meanings experimenters assign to gesture are the meanings the speaker

Box 3. Spontaneously produced gestures

McNeill (Ref. a) has identified a number of different types of gestures that speakers routinely use when they talk:

(1) 'Iconic' gestures transparently capture aspects of the semantic content of speech. For example, when describing how water was poured from a glass into a dish, a child arced her fist in the air as though pouring from one container to another.

(2) 'Metaphoric' gestures are like iconics in that they are pictorial; however, the pictorial content is abstract rather than concrete. For example, when announcing that what he is about to narrate is a cartoon, a speaker raised his hands as though offering the listener an object. Just as we speak metaphorically about 'presenting' an idea or argument, gesture makes an abstract entity (the cartoon) concrete by treating it as a bounded object supported by the hands and presented to the listener.

(3) 'Beat' gestures look as though they are beating musical time. The hand moves along with the rhythmical pulsation of speech. Unlike iconics and metaphorics, beats tend to have the same form regardless of the content (a simple flick of the hand or fingers up and down, or back and forth).

(4) 'Deictic' or pointing gestures indicate entities in the conversational space, but they can also be used even when there is nothing to point at. For example, a speaker asked '*where did you come from before?*' while pointing at a space in the room. The space was not, in fact, the listener's former location but, over the course of the conversation, had come to represent that location.

It is relatively easy to develop a gestural 'lexicon' for a particular task. The lexicon can then be used to code gesture and its relation to speech in subsequent data. For example, consider gesture produced during a liquid conservation task. Meaning is assigned to each gesture on the basis of the shape and placement of the hand and form of the motion in relation to its accompanying speech. A flat palm held horizontally without movement at the water level of a container is the gesture that typically accompanies height explanations in speech ('*it's tall*'); the meaning 'height' is therefore assigned to this gesture form. The form–meaning pairings that result from this process are then used to code gestures produced by other children performing this same task.

To ensure independence of the gesture and speech codes, one experimenter codes gesture without listening to the accompanying speech (i.e. with the sound turned off) and another codes speech without watching gesture (i.e. with the picture turned off). A response is considered a gesture–speech mismatch if, in separate passes through the data, the meaning assigned to gesture is different from the meaning assigned to speech. If, for example, gesture is assigned the meaning 'height' by one coder and the accompanying speech is assigned the meaning 'width' by another, the response as a whole is considered a mismatch.

Reliability between two experimenters, each of whom transcribes the same videotape independently, is typically high for coding speech, gesture, and the relationship between the two (e.g. on conservation tasks, agreement between two coders ranges from 85% to 94%) (Ref. b).

References

a McNeill, D. (1992) *Hand and Mind*, University of Chicago Press
b Goldin-Meadow, S. and Sandhofer, C.M. (1999) Gesture conveys substantive information about a child's thoughts to ordinary listeners *Dev. Sci.* 2, 67–74

intends. Consider a child asked to complete an 'explanation task' in which she explains her solutions to a set of math problems and, later, a 'rating task' in which she judges solutions to a second set of problems. If gesture is a vehicle through which speakers express their knowledge – and if experimenters can correctly assess this knowledge when attributing problem-solving procedures to children based on their gestures in the explanation task – then, on the rating task, the child should judge procedures she expressed on the explanation task in gesture as more 'acceptable' than procedures she did not express at all. Children were found to do just that – even when those procedures were expressed only in gesture and not anywhere in speech[27]. In addition to underscoring an important methodological point (that experimenters' interpretations of gesture are valid), these findings confirm an important conceptual point – that gestures are not random movements but rather reveal substantive beliefs about the task at hand.

Gesture can reflect thoughts not conveyed in speech

Speakers use gesture to depict notions ranging from the concrete (e.g. the actions or attributes of cartoon characters) to the abstract (e.g. mathematical notions, such as quotients, factors, and even limits in calculus)[28]. Because gesture rests on different representational devices from speech, and is not dictated by standards of form as is speech, it has the potential to offer a different view into the mind of the speaker. Gesture permits the speaker to represent ideas that are compatible with its mimetic and analog format (e.g. shapes, sizes, spatial relationships) – ideas that may be less compatible with the discrete and categorical format underlying speech. Thus, when it accompanies speech, gesture allows speakers to convey thoughts that may not easily fit into the categorical system that their spoken language offers[29]. For example, the gestures accompanying a description of the East Coast of the United States can convey aspects of the coastline that would be difficult, if not impossible, to convey in speech. Gesture then has the potential to display thoughts that are not conveyed in the speech it accompanies (gesture also provides prelinguistic children with a vehicle for expressing thoughts they do not yet have words for, see Box 4).

Consider a six-year-old child attempting to justify his (incorrect) belief that number changes when one of two identical rows of checkers is spread out. The child says that the number of checkers in the spread-out row is now 'different because you moved them', thus making it clear, in speech, that he has focused on what was done to the checkers. However, in the gestures accompanying this utterance, the child indicates some understanding of the one-to-one correspondence that can be established between the two rows of checkers – he moves a pointing hand back-and-forth between the two rows, pairing the first checker in row 1 with the first checker in row 2, and so on[30]. The child speaks about how the checkers were moved, but he has also noticed – not necessarily consciously

Box 4. Gesture is a precursor to speech

At a time when children are limited in what they can say, there is another avenue of expression open to them, one that can extend the range of ideas they are able to express. Children can gesture. The earliest gestures children use, typically beginning around 10 months and prior to their first words, are 'deictics' (Ref. a). For example, a child holds up an object to draw an adult's attention to that object or, later in development, points at the object. At the same time, some children also use 'iconic' gestures. For example, a child opens and closes her mouth to represent a fish, or flaps her hands to represent a bird (Refs b,c). 'Metaphoric' and 'beat' gestures are not produced before speech, and do not appear until later in development (see also Box 3).

Combining gesture and speech within a single utterance can also increase the communicative range available to children. Most of the gesture–speech combinations that young children produce contain gestures that convey information *redundant* to the information conveyed in speech; for example, pointing at an object while naming it. However, young children also produce gesture–speech combinations in which gesture conveys information that is *different* from the information conveyed in speech; for example, gesturing at an object while describing the action to be done on the object in speech (pointing to an apple and saying '*give*'), or gesturing at an object and describing the owner of that object in speech (pointing at a toy and saying '*mine*') (Refs d–g).

Children begin producing gesture–speech combinations prior to their first two-word utterances. More impressive is the fact that the age at which children first produce combinations in which gesture and speech convey different information (e.g. '*give*' + point at apple) predicts the age at which they produce their first word–word combinations ('*give apple*') (Ref. h). Thus, the ability to use gesture and speech together to convey different components of a proposition is a harbinger of the ability to convey those components solely within speech.

Given theories about the importance of gesture in the origins of language (Refs i,j), it is interesting to note that chimpanzees in the wild do not use gesture as human children do (Ref. k). Chimps use gesture to request here-and-now action of another chimp (e.g. raising their arms over their heads to invite another chimp to groom them) (Ref. l). In contrast, children use gesture, not only to request, but also to comment on objects in their surrounds (e.g. pointing to comment on distant events). Even chimps who are raised by humans do not interpret points referentially (i.e. they do not understand that the point is about a particular object); rather, they learn to respond to the gesture in such a way that they can garner a food reward (Ref. m). Finally, although chimps who have been taught a communication system do gesture, they rarely use those gestures (or, for that matter, the system they have been taught) to comment (Ref. n). Thus, gesture may serve as a way-station on the road to language, both over ontogenetic and evolutionary time.

References

a Bates, E. *et al.* (1979) *The Emergence of Symbols: Cognition and Communication in Infancy*, Academic Press

b Acredolo, L.P. and Goodwyn, S.W. (1985) Symbolic gesture in language development: a case study *Hum. Dev.* 28, 40–49

c Iverson, J.M., Capirci, O. and Caselli, M.S. (1994) From communication to language in two modalities *Cognit. Dev.* 9, 23–43

d Goldin-Meadow, S. and Morford, M. (1985) Gesture in early child language: studies of deaf and hearing children *Merrill-Palmer Quarterly* 31, 145–176

e Greenfield, P. and Smith, J. (1976) *The Structure of Communication in Early Language Development*, Academic Press

f Morford, M. and Goldin-Meadow, S. (1992) Comprehension and production of gesture in combination with speech in one-word speakers *J. Child Lang.* 9, 559–580

g Zinober, B. and Martlew, M. (1985) Developmental changes in four types of gesture in relation to acts and vocalizations from 10 to 21 months *Br. J. Dev. Psychol.* 3, 293–306

h Goldin-Meadow, S. and Butcher, C. Pointing toward two-word speech in young children, in *Pointing: Where Language, Culture, and Cognition Meet* (Kita, S., ed.), Cambridge University Press (in press)

i Hewes, G.W. (1973) Primate communication and the gestural origin of language *Curr. Anthropol.* 14, 5–24

j Donald, M. (1991) *Origins of the Modern Mind: Three Stages in the Evolution of Culture and Cognition*, Harvard University Press

k Tomasello, M. and Camaioni, L. (1997) A comparison of the gestural communication of apes and human infants *Hum. Dev.* 40, 7–24

l Plooij, F.X. (1978) Some basic traits of language in wild chimpanzees?, in *Action, Gesture and Symbol: The Emergence of Language* (Lock, A., ed.), pp. 111–131, Academic Press

m Povinelli, D. *et al.* (1997) Exploitation of pointing as a referential gesture in young children, but not adolescent chimpanzees *Cognit. Dev.* 2, 423–461

n Greenfield, P.M. and Savage-Rumbaugh, E.S. (1991) Imitation, grammatical development and the invention of protogrammar by an ape, in *Biological and Behavioral Determinants of Language Development* (Krasnegor, N.A. *et al.* eds), pp. 235–262, Earlbaum

– that the spread-out row can be aligned with the untouched row. This insight is one that the child expresses only through his hands.

This child has produced a gesture–speech mismatch – a communicative act in which the information conveyed in gesture is different from the information conveyed in the accompanying speech. Gesture–speech mismatches are not unique to conservation or to six-year-olds, however. We find the same phenomenon in nine-year-old children asked to explain their solutions to mathematical equivalence problems such as 4+5+3+__=+3 (Ref. 31). For example, a child says, 'I added 4 plus 5 plus 3 plus 3 and got 15', demonstrating no awareness of the fact that this is an equation bifurcated by an equal sign. Her gestures, however, offer a different picture: she sweeps her left palm under the left side of the equation, pauses, then sweeps her right palm under the right side. The child's gestures clearly demonstrate that, at some level, she knows the equal sign breaks the string into two parts. Mismatches have also been found in toddlers[32], preschoolers[33], adolescents[34] and even adults[35]. Nor are mismatches restricted to number puzzles – they arise in spontaneous talk[36], narratives[21], reasoning about physics problems[37], moral dilemmas[38] and many other contexts.

In a mismatch, a speaker conveys two distinct ideas about the very same problem. But the explanations in which gestures are produced often come after the fact. Do speakers who produce mismatches in their post hoc explanations of a problem also activate two ideas when solving that problem on-line? The evidence suggests that they do (Box 5) – mismatchers activate more than one idea, not only when explaining a math problem, but also when solving that same type of math problem. The cognitive state that underlies mismatch thus involves having, and activating, more than one idea on a single task.

Box 5. How do gesture–speech mismatchers solve problems on-line?

If explanations are an accurate reflection of the processes that take place in problem-solving, mismatching children, who produce two procedures on each explanation of their math problems (one in speech and a second in gesture), should also activate two procedures when solving each problem. In contrast, matching children, who produce a single procedure per explanation, ought to activate only one procedure when solving each problem. If so, mismatchers work harder to arrive at their incorrect answers than matchers, and should have less cognitive effort left over to tackle other tasks.

Goldin-Meadow *et al.* (Ref. a) tested this prediction by first asking children to solve and explain a series of mathematical equivalence problems. Their explanations were used to divide children into matchers and mismatchers. Children then participated in another math task and a concurrent word recall task. On each trial, children were given a list of words to remember, either a one-word list (which was not expected to tax cognitive capacity) or a three-word list (which was more likely to strain capacity). Children were also given a math problem to solve while remembering the words – either a hard problem (e.g. 3+6+7+__=+8) which tends to elicit two-procedure explanations from mismatchers, and one-procedure explanations from matchers; or an easy problem (e.g. 4+7+3+5=__) which elicits one-procedure explanations from all children.

'Easy' problems were indeed easy, and were solved correctly by all children (Fig. I). 'Hard' problems were hard and solved by none, irrespective of whether the problems were solved along with one- versus three-word lists. The key finding involves the proportion of word lists the children recalled correctly as a function of the type of math problem (easy or hard) that accompanied the task (Fig. IB). Three points are noteworthy:

(1) Both matching and mismatching children were expected to activate a single procedure per problem when solving easy math problems. They should thus expend the same amount of effort on these problems and should recall the same proportion of word lists after solving them – as indeed they did.

(2) Matchers were also expected to activate a single procedure when solving hard math problems. Their performance on word recall should therefore not differ for easy versus hard problems – and it did not.

(3) In contrast, mismatchers were expected to active two procedures when solving hard math problems. They should therefore have less capacity left over to recall words after solving these problems and should perform poorly on this task, particularly when capacity is taxed on the three-word lists. As predicted, mismatchers recalled significantly fewer three-word lists after solving hard math problems than did matchers.

Thus, when solving the hard math problems, mismatchers carry the extra burden of too many unintegrated ideas, a burden which appears to take cognitive effort, leaving less effort available for other tasks.

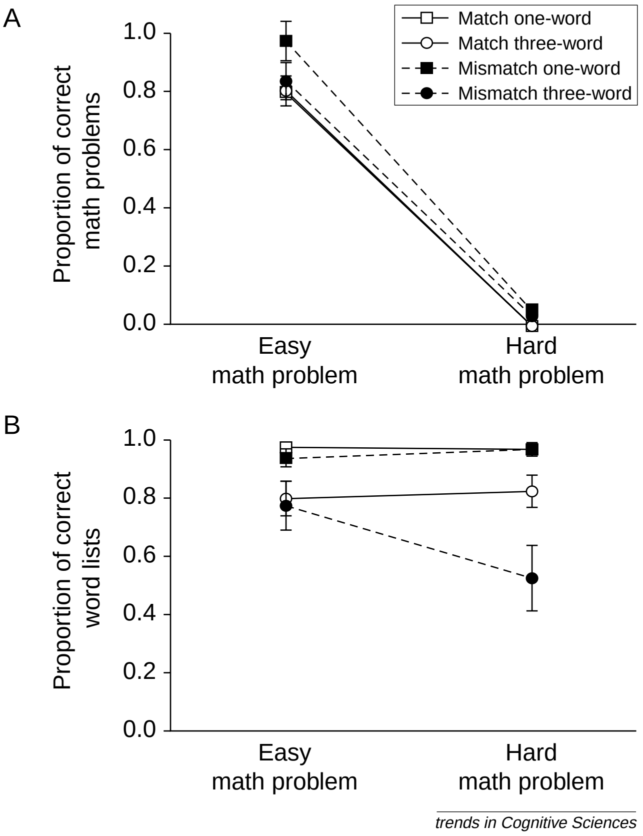

Fig. I. Performance on math problems and a concurrently administered word-recall task. (A) The proportion of easy (e.g. 4+7+3+5=__) and hard (e.g. 3+6+7+__=+8) math problems that were solved correctly by matching and mismatching children while simultaneously recalling one- versus three-word lists. (Solid lines, data referring to matching children; broken lines, data referring to mismatching children; error bars indicate SE.) All children solved the 'easy' problems correctly but none solved the 'hard' problems. **(B)** The proportion of one- and three-word lists that were recalled correctly by matching and mismatching children while simultaneously solving easy versus hard math problems. (Symbols and lines the same as in A.) Mismatching children's recall differed from matching children's recall only on three-word lists and only when solving hard math problems. (Modified from Ref. a.)

Reference

a Goldin-Meadow, S. *et al.* (1993) Transitions in learning: evidence for simultaneously activated strategies *J. Exp. Psychol.* 19, 92–107

Gesture can index cognitive instability

Gesture–speech mismatch is of particular interest to researchers because it is a characteristic of learners who are in transition with respect to a task. Children who produce a relatively large proportion of gesture–speech mismatches when explaining their (incorrect) solutions to a task are particularly likely to benefit from instruction in that task – significantly more than children who produce few mismatches. Mismatch has been found to be a reliable index of readiness-to-learn in conservation[30] and mathematical equivalence[31] tasks. Thus, when children produce mismatches, they are 'at risk' for learning. They are also, however, at risk for regression. The same proportion of children who progress to a stable correct state when given instruction in the math task, regress to a stable *incorrect* state when given no instruction[39]. Mismatchers are apparently in a state of cognitive instability, open to instruction if it is provided but vulnerable to regression if it is not.

If mismatch is indeed a transitional period, we would expect learners to proceed from a stable state, through mismatch, to another stable state but at a higher level. Microgenetic methods were developed so that learners' progress could be systematically monitored around periods of greatest change[40]. Alibali and Goldin-Meadow[39] used the technique to chart the course of children's development of mathematical equivalence over the short term. They instructed children individually and observed each child's step-by-step progress. Focusing on children who gestured, they found that almost all of the children passed through two, or even three, of the following steps in order: (1) a stable state in which the child produced gesture–speech matches conveying incorrect procedures; (2) an unstable state in which the child produced

Table 1. Gesture–speech matches and mismatches used by children as they progress towards mastery in two tasks

Modality	Matching explanations (incorrect)	Mismatching explanations (both incorrect)	Matching explanations (correct)
Sample responses to the mathematical equivalence problem 6+4+7=__+7			
Speech	'I added the 6, the 4 and the 7' (add-to-equal-sign)	'I added the 6, the 4 and the 7' (add-to-equal-sign)	'I made this side equal to that side' (equalize-two-sides)
Gesture	Points at 6, 4 and and left 7 (add-to-equal-sign)	Points at 6, 4, left 7 and right 7 (add-all-numbers)	Palm sweeps under left side then under right (equalize-two-sides)
Sample responses to a liquid-conservation task[a]			
Speech	'This one's tall and this one's short' (comparison of heights)	'This one's tall and this one's short' (comparison of heights)	'This one's tall but it's skinny' (compensation)
Gesture	Flat palm marks water level of glass then water level of dish (comparison of heights)	Narrow C demarcates width of glass then wider C demarcates width of dish (comparison of widths)	Flat palm marks water level of glass then narrow C demarcates its width (compensation)

[a]*In this task, water is poured from a tall, thin glass into a short, wide dish.*

gesture–speech mismatches; (3) a stable state in which the child again produced gesture–speech matches, now conveying correct procedures.

Thus, as predicted, children tended to proceed through mismatch in acquiring mathematical equivalence. Interestingly, the few children who skipped the mismatching state and progressed directly from an incorrect to a correct matching state were less able to generalize their knowledge than the children who passed through the mismatching state. Skippers appear to learn the concept less thoroughly than those who pass through mismatch.

Is gesture in advance of speech when children are in a mismatching state? Mismatchers' gestures often convey ideas that are more developed than those they convey in speech[41], as illustrated in the math and conservation examples presented thus far. But speech can also convey the mature ideas while gesture lags behind, as is typically found in moral judgment tasks[38]. Finally, gesture and speech can both convey incorrect notions, albeit different ones, as illustrated in the mismatching examples in Table 1.

Why might mismatch be associated with transition and learning? Mismatch is an index of variability, and variability is considered by many theorists to be essential to developmental progress[42,43]. A number of studies have demonstrated variability in children's repertoires across problems (e.g. one procedure is used to solve a problem at time 1, and another is used to solve the problem at time 2)[44,45]. Gesture–speech mismatch is unique in that it reflects within-problem variability – the child produces two different procedures, one in speech and the other in gesture, on the problem at the same time. Activating two procedures on the same problem may be essential for eventually coordinating the two procedures, or resolving the conflict between them. It turns out, however, that children who produce a large number of mismatches also tend to have across-problem variability – they have more different kinds of ideas in their repertoires than children who produce few mismatches. Moreover, the 'extra' ideas that mismatchers have are found *only* in gesture and not in speech (Box 6). Thus, the variability that may make mismatchers particularly vulnerable to instruction can only be detected by looking at the children's hands, not by listening to their words.

Do gestures communicate to listeners?

We have seen that gesture can communicate unique information about a learner's state, and that researchers have begun to take advantage of this 'window' to the mind. The question is whether the information displayed in gesture is accessible to ordinary listeners not trained in laboratory settings.

This is a controversial question. On the one hand, Kendon[46] concludes that listeners do attend to gesture and alter their understanding of utterances accordingly. On the other hand, Krauss and his colleagues[47] argue that gesture has little communicative value. However, many of the relevant studies do not control the type of speech that accompanies gesture; without such control it is often difficult to demonstrate definitively that gesture is influencing understanding. Other studies narrow the field too much, exploring only gestures that are selected by observers to be completely redundant with the speech they accompany. Indeed, not enough attention has been paid to gesture that conveys different information from speech. One might expect that it is precisely in situations of gesture–speech mismatch that gesture can play its largest role in communication.

A number of recent studies have found that ordinary listeners can reliably 'read' gesture when it conveys different information from speech[48–52], even when gesture is unedited and fleeting, as it is in natural communication[53]. Take, for example, an untrained adult asked to assess the child described earlier who, in speech, focused on how the checkers were moved but, in gesture, highlighted the one-to-one alignment

Box 6. Gesture–speech mismatchers have variable problem-solving repertoires

Recent research has shown that, at a single moment in time, children frequently have in their repertoires a variety of strategies or approaches to a problem (Refs a–d). Children who tend to produce gesture–speech mismatches produce more than one notion on a single problem and, in this sense, are variable in their responses. However, do these children also have variability in their repertoires when taken as a whole? To address this question, Goldin-Meadow, Alibali and Church (Ref. e) determined how many different problem-solving procedures a child produced across a set of six math problems. They also determined the modality (or modalities) in which each different procedure was produced: in speech and never in gesture; in gesture and never in speech; or in both speech and gesture (although not necessarily on the same problem). The calculations were done separately for children who produced a large proportion of mismatches, and for children who produced few mismatches. Overall, mismatchers produced significantly more different kinds of procedures than matchers (Fig. I). They thus had more variability in their repertoires, which might well account for their 'vulnerability' to instruction.

In terms of modalities in which these procedures appeared, it is interesting to note that neither group of children produced many procedures in speech alone. Almost all of the information that the children possessed about this task was accessible to gesture, either with or without speech. The groups also did not differ in the number of different procedures they produced in both speech and gesture. Where the groups did differ, however, was in the number of different procedures they produced in gesture alone. The mismatchers produced signifcantly more procedures in gesture (and not in speech) than the matchers. Thus, the 'extra' procedures that the mismatchers had in their repertoires were all unique to gesture.

References

a Adolph, K.E. (1997) Learning in the development of infant locomotion *Monogr. Soc. Res. Child Dev.* 62

b Siegler, R.S. (1996) *Emerging Minds: The Process of Change in Children's Thinking*, Oxford University Press

c Siegler, R.S. and McGilly, K. (1989) Strategy choices in children's time-telling, in *Time and Human Cognition: A Life Span Perspective* (Levin, I. and Zakay, D., eds), pp. 185–218, Elsevier

d Siegler, R.S. (1999) Strategic development *Trends Cognit. Sci.* 3, 430–435

e Goldin-Meadow, S., Alibali, M.W. and Church, R.B. (1993) Transitions in concept acquisition: using the hand to read the mind *Psychol. Rev.* 100, 279–297

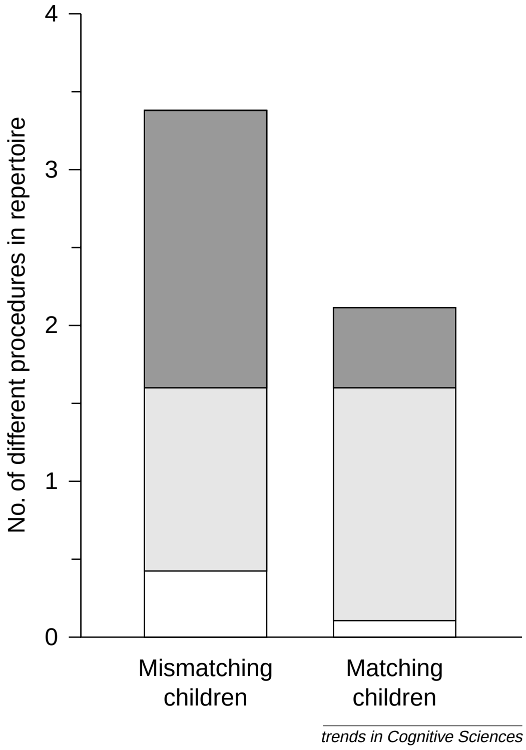

Fig. I. Number of different problem-solving procedures in the repertoires of mismatching and matching children. A procedure was classified as a function of the modality (or modalities) in which it was produced by a child across six problems. Overall, mismatchers produced significantly more types of procedures than matchers, although the distribution varied in the two groups, particularly in procedures produced in gesture but not speech (dark grey). Procedures in speech and gesture, light grey; procedures in speech but not gesture, white. (Adapted from Ref. e.)

between the checkers in the rows. The adult attributed to this child reasoning based not only on the fact that the checkers had been moved, but also on one-to-one correspondence. Ordinary listeners can thus take advantage of the unique insight gesture offers into the thoughts speakers have, but do not express in words.

Given that a listener can extract substantive information from gesture, it is perhaps not surprising that speech can be affected by the gestural company it keeps. Gesture can facilitate comprehension of a spoken message when it conveys that same message (gesture–speech match). But gesture can also impede comprehension of a spoken message when it conveys a different message (gesture–speech mismatch). Gesture is clearly part of the communicative process, one that at times can lead the listener astray (Box 7).

To summarize thus far, gesture not only conveys substantive information to well-trained coders who have the advantage of time and instant replay on their side, but it also conveys information to naive listeners. Listeners glean meaning from gesture which, in turn, has an effect on how the meaning conveyed in the accompanying speech is interpreted. Gesture thus has the potential to play a role in cognitive change. Gesture can signal to those who interact with a learner that a particular notion is in the learner's repertoire. Listeners may then alter their behavior accordingly, perhaps giving explicit instruction in that notion if it is correct, or providing input that encourages the learner to abandon the notion if it is misguided. If gesture can play this type of role in spontaneous interaction, learners may be able to shape the day-to-day input they receive just by moving their hands.

Do gestures function for speakers?

We have been proceeding as though communication is gesture's only function – but is it? The fact that gestures communicate to listeners does not preclude the possibility that gesture functions for speakers as well. After all, speakers gesture when

Box 7. Teachers gesture in math tutorials and children pay attention

Gesture is understood by listeners asked to observe, but not participate, in an interaction. However, in order to argue that gesture plays an important role in communication, it is essential to demonstrate that listeners can 'read' gesture when they themselves are participants in the conversation. Goldin-Meadow, Kim and Singer (Ref. a) asked teachers to instruct a series of children individually in mathematical equivalence and videotaped the tutorials. As the teachers did most of the talking – and gesturing – in the interactions, the experimenters explored how the children responded to the problem-solving procedures that teachers produced in speech and gesture. A child was conservatively assumed to understand the teacher's procedure when the child responded by repeating or paraphrasing that procedure.

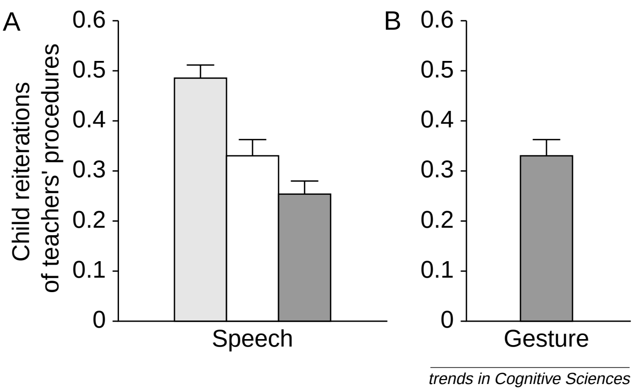

Fig. I. Mean proportion of child reiterations of teachers' problem-solving procedures. (A) The proportion of child reiterations following the teacher's speech when accompanied by matching gesture (light grey), no gesture (white), or mismatching gesture (dark grey). (Error bars indicate SE.) **(B)** The proportion of child reiterations following the teacher's gesture when accompanied by mismatching speech (i.e. gesture component of a mismatch). Child reiterations followed procedures produced in the gesture component of a mismatch 20% of the time – approximately as often as they followed procedures produced in the speech component. (Modified from Ref. a.)

Gesture was found both to help and to undermine the child's comprehension of teacher speech (Fig. IA). Children were *more* likely to repeat a procedure the teacher produced in speech when that speech was accompanied by a matching gesture than when it was accompanied by no gesture at all. When gesture conveys the same message as speech, perhaps not surprisingly, it helps the listener arrive at that message. Conversely, children were *less* likely to repeat a procedure the teacher produced in speech when that speech was accompanied by a mismatching gesture than when it was accompanied by no gesture at all. When gesture conveys a different message from speech, it detracts from the listener's ability to arrive at the message in speech.

Were children able to glean substantive information from the teacher's gestures? When the teacher procedures were expressed uniquely in gesture (i.e. in the gesture component of a mismatch) children reiterated these procedures 20% of the time (Fig. IB). Although this might seem like a small proportion, note that child reiterations followed teacher procedures produced uniquely in *speech* only 25% of the time (compare the dark grey bars in Fig. IA and B). Moreover, children frequently 'translated' procedures that the teacher produced uniquely in gesture into their own speech, thus clearly demonstrating that they fully understood their meaning. Children were able to glean information from teachers' gestures even when they were active participants in the interaction.

Indeed, there is anecdotal evidence fom the videotaped teacher–child tutorials that children zero in on a teacher's gestures, sometimes to their own disadvantage. For example, while telling a child to make both sides of the equation 4+6+7+__=7 equal, a teacher inadvertently pointed at the four numbers in the problem – a series of gestures children typically produce when they add all of the numbers to get the solution. The child ignored the teacher's speech and focused on her gestures. In the next turn, much to the teacher's surprise, the child gave 24 as his solution, the solution obtained by adding up all four numbers. Gesture is a potentially powerful source of input for children and adults alike.

Reference

a Goldin-Meadow, S., Kim, S. and Singer, M. What the teacher's hands tell the student's mind about math *J. Educ. Psychol.* (in press)

no one is watching[54]. Indeed, blind speakers gesture routinely, even though they themselves have never seen gesture – and they do so even when they are knowingly speaking with listeners who are themselves blind[55].

Gesture plays a variety of roles for speakers. Gesture helps speakers retrieve words from memory[56]. Gesture reduces cognitive burden, thereby freeing up effort that can be allocated to other tasks. For example, pointing improves young children's performance on counting tasks particularly if the pointing is done by the children themselves[57]. As another example, gesturing while explaining a math task improves performance on a simultaneously performed word recall task[58]. Gesturing thus appears to increase resources available to the speaker, perhaps by shifting the burden from verbal to spatial memory.

Gesture may also provide a route through which learners can access new thoughts. For example, children participating in science lessons frequently use gesture to foreshadow the ideas they themselves eventually articulate in speech[59] perhaps needing to express those ideas in a manual medium before articulating them in words. Because the representational formats underlying gesture are mimetic and analog rather than discrete[21], gesture may permit the learner to represent ideas that lend themselves to these formats and that are not yet developed enough to be encoded in speech. Take, for example, the child described earlier who demonstrated a clear understanding of the one-to-one correspondence between checkers in his gestures, but seemed unable to articulate this notion in speech. The ease with which the two rows of checkers can be paired in gesture may have facilitated the child's expression of this notion. Once having entered the child's repertoire, this new-found idea can begin to change the system. At some point, the child will have to reconcile his belief that the number of checkers changed with the fact that the checkers in the moved and unmoved rows can be put into one-to-one alignment. By offering an alternative route in which developing ideas can be tried out and expressed, gesture may itself facilitate the process of change.

Gesture may also have an advantage over speech in that novel (and perhaps contradictory) information can be brought into a learner's repertoire without disrupting the current system. Spontaneous gestures are not part of a culturally recognized system and thus rarely are subject to comment and criticism. As a result, gesture is an ideal modality within which to consider for the first time notions that are not fully developed. Not only are the notions conveyed in gesture likely to go unchallenged by others, but they are also likely to go unchallenged by oneself. A speaker can unknowingly 'sneak in' an idea in gesture that does not cohere well with the set of ideas the speaker routinely expresses in speech. Gesture may be a perfect place to try out innovative ideas

Outstanding questions

- Deaf children of hearing parents can invent the rudiments of a language-like system without the benefit of a conventional language model, or even a willing communication partner (the children's hearing parents are committed to teaching them to speak). How far can an individual child (as opposed to a society) go in fashioning a linguistic system out of gesture? Are there certain types of constructions and uses that can only be introduced into a language system with group support?
- What are the forces that shape the particular linguistic patterns found in the deaf children's gesture systems? They are not shaped by conventional language, nor are they modeled after their hearing parents' spontaneous gestures. One possibility is that the patterns reflect the way children structure events in general or, more specifically, the way they structure events for the purposes of communication.
- The spontaneous gestures that speakers use along with their talk do not feel as though they are consciously produced – one is not typically aware of having gestured. What would happen if speakers were forced to be aware of their gestures? Would those gestures no longer have privileged access to the speaker's unspoken thoughts?
- What are the contexts in which listeners are able to 'read' gesture? Listeners typically have difficulty apprehending both of the messages conveyed in a mismatch (the message in speech, and the message in gesture). What determines which of the two messages will be read? Are there conditions under which listeners can grasp both messages?
- Does gesturing help speakers think? There is growing evidence that gesture can facilitate word recall and help conserve cognitive effort. Are these effects limited to certain types of domains – the spatial domain, for example, which the manual modality is particularly well-suited to portray?

simply because neither listener nor speaker is consciously aware of the fact that those ideas do not fit.

Conclusion

When gesture is called upon to fulfill the burdens of a primary communication system – that is, when it is explicitly communicative – it takes on the forms of language, conveying meaning by systematic combinations of discrete units. However, when gesture is used spontaneously along with speech – when it is not an acknowledged vehicle of communication – it is not language-like in form, and assumes instead a mimetic and analog format that allows it to capture ideas not easily expressed in speech. As such, the gestures that accompany speech have the potential to display thoughts that are not conveyed in speech. These speech-accompanying gestures serve two, not mutually exclusive functions. Gesture provides speakers with another representational format in addition to speech, one that can reduce cognitive effort and serve as a tool for thinking. Gesture also provides listeners with a second representational format, one that allows access to the unspoken thoughts of the speaker and thus enriches communication.

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References

1 Ekman, P. and Friesen, W.V. (1969) The repertoire of non-verbal behavior: categories, origins, usage and coding *Semiotica* 1, 49–98
2 Kendon, A. (1981) Geography of gesture *Semiotica* 37, 129–163
3 Bellugi, U. and Studdert-Kennedy, M., eds (1980) *Signed and Spoken Language: Biological Constraints on Linguistic Form*, Verlag Chemie
4 Klima, E. and Bellugi, U. (1979) *The Signs of Language*, Harvard University Press
5 Lane, H. and Grosjean, F., eds (1980) *Recent Perspectives on American Sign Language*, Erlbaum
6 Lidell, S. (1980) *American Sign Language Syntax*, Mouton
7 Lillo-Martin, D. (1991) *Universal Grammar and American Sign Language: Setting the Null Argument Parameters*, Kluwer
8 Supalla, T. (1986) The classifier system in American Sign Language, in *Noun Classes and Categorization* (Craig, C., ed.), pp. 181–215, John Benjamins
9 Supalla, T. and Newport, E.L. (1978) How many seats in a chair? The derivation of nouns and verbs in American Sign Language, in *Understanding Language through Sign Language Research* (Siple, P., ed.), pp. 91–132, Academic Press
10 Corina, D. and Sandler, W. (1993) On the nature of phonological structure in sign language *Phonology* 10, 165–207
11 Perlmuttter, D.M. (1992) Sonority and syllable structure in American Sign Language *Linguist. Inq.* 23, 407–442
12 Padden, C. and Perlmutter, D (1987) American Sign Language and the architecture of phonological theory *Nat. Lang. Linguist. Theory* 5, 335–375
13 Frishberg, N. (1975) Arbitrariness and iconicity: historical change in American Sign Language *Language* 51, 696–719
14 Tervoort, B.T. (1961) Esoteric symbolism in the communication behavior of young deaf children *Am. Ann. Deaf.* 106, 436–480
15 Moores, D.F. (1974) Nonvocal systems of verbal behavior, in *Language Perspectives* (Schiefelbusch, R.L. and Lloyd, L.L., eds), pp. 377–417, University Park Press
16 Goldin-Meadow, S. *et al.* (1994) Nouns and verbs in a self-styled gesture system: what's in a name? *Cognit. Psychol.* 27, 259–319
17 Goldin-Meadow, S., Mylander, C. and Butcher, C. (1995) The resilience of combinatorial structure at the word level: morphology in self-styled gesture systems *Cognition* 6, 195–262
18 Morford, J.P. and Goldin-Meadow, S. (1997) From here to there and now to then: the development of displaced reference in homesign and English *Child Dev.* 68, 420–435
19 Goldin-Meadow, S. (1997) The resilience of language in humans, in *Social Influences on Vocal Development* (Snowdon, C.T. and Hausberger, M., eds), pp. 293–311, Cambridge University Press
20 Singleton, J.L., Morford, J.P. and Goldin-Meadow, S. (1993) Once is not enough: standards of well-formedness in manual communication created over three different timespans *Language* 69, 683–715
21 McNeill, D. (1992) *Hand and Mind*, University of Chicago Press
22 Goldin-Meadow, S. and Mylander, C. (1983) Gestural communication in deaf children: the non-effects of parental input on language development *Science* 221, 372–374
23 Goldin-Meadow, S., McNeill, D. and Singleton, J. (1996) Silence is liberating: removing the handcuffs on grammatical expression in the manual modality *Psychol. Rev.* 103, 34–55
24 Friedman, H.S. (1979) The concept of skill in nonverbal communication: implications for understanding social interaction, in *Skill in Nonverbal Communication* (Rosenthal, R., ed.), pp. 2–27, Oelgeschlager, Gunn & Hain
25 Kendon, A. (1980) Gesticulation and speech: two aspects of the process of utterance, in *Relationship of Verbal and Nonverbal Communication* (Key, M.R., ed.), pp. 207–228, Mouton
26 Crowder, E.M. and Newman, D. (1993) Telling what they know: the role of gesture and language in children's science explanations *Pragmat. Cognit.* 1, 341–376
27 Garber, P., Alibali, M.W. and Goldin-Meadow, S. (1998) Knowledge conveyed in gesture is not tied to the hands *Child Dev.* 69, 75–84
28 McNeill, D. (1987) *Psycholinguistics: A New Approach*, Harper & Row
29 Goldin-Meadow, S. and McNeill, D. (1999) The role of gesture and mimetic representation in making language the province of speech, in *The Descent of Mind* (Corballis, M.C. and Lea, S., eds), pp. 155–172, Oxford University Press
30 Church, R.B. and Goldin-Meadow, S. (1986) The mismatch between gesture and speech as an index of transitional knowledge *Cognition* 23, 43–71
31 Perry, M., Church, R.B. and Goldin-Meadow, S. (1988) Transitional knowledge in the acquisition of concepts *Cognit. Dev.* 3, 359–400
32 Gershkoff-Stowe, L. and Smith, L.B. (1997) A curvilinear trend in naming errors as a function of early vocabulary growth *Cognit. Psychol.* 34, 37–71

33 Evans, M.A. and Rubin, K.H. (1979) Hand gestures as a communicative mode in school-aged children *J. Gen. Psychol.* 135, 189–196

34 Stone, A., Webb, R. and Mahootian, S. (1992) The generality of gesture–speech mismatch as an index of transitional knowledge: evidence from a control-of-variables task *Cognit. Dev.* 6, 301–313

35 Schwartz, D.L. and Black, J.B. (1996) Shuttling between depictive models and abstract rules: induction and fallback *Cognit. Sci.* 20, 457–497

36 Goldin-Meadow, S. (1998) The development of gesture and speech as an integrated system, in *The Nature and Functions of Gesture in Children's Communications* in *New Directions for Child Development* (No. 79) (Iverson, J.M. and Goldin-Meadow, S., eds), pp. 29–42, Jossey–Bass

37 Alibali, M.W. *et al*. (1999) Illuminating mental representations through speech and gesture *Psychol. Sci.* 10, 327–333

38 Church, R.B. *et al*. (1995) The role of gesture and speech communication as reflections of cognitive understanding *J. Contemp. Legal Iss.* 6, 123–154

39 Alibali, M.W. and Goldin-Meadow, S. (1993) Gesture–speech mismatch and mechanisms of learning: what the hands reveal about a child's state of mind *Cognit. Psychol.* 25, 468–523

40 Siegler, R.S. and Crowley, K. (1991) The microgenetic method: a direct means for studying cognitive development *Am. Psychol.* 46, 606–620

41 Goldin-Meadow, S., Alibali, M.W. and Church, R.B. (1993) Transitions in concept acquisition: using the hand to read the mind *Psychol. Rev.* 100, 279–297

42 Siegler, R.S. (1994) Cognitive variability: a key to understanding cognitive development *Curr. Dir. Psychol. Sci.* 3, 1–5

43 Thelen, E. (1989) Self-organization in developmental processes: can systems approaches work?, in *Systems and Development: The Minnesota Symposium on Child Psychology* (Gunnar, M. and Thelen, E., eds), pp. 77–117, Erlbaum

44 Piaget, J. (1952) *The Child's Conception of Number*, Humanities Press

45 Strauss, S. (1972) Inducing cognitive development and learning: a review of short-term training experiments: I. The organismic developmental approach *Cognition* 1, 329–357

46 Kendon, A. (1994) Do gestures communicate?: a review *Res. Lang. Soc. Interact.* 27, 175–200

47 Krauss, R.M., Morrel-Samuels, P. and Colasante, C. (1991) Do conversational hand gestures communicate? *J. Pers. Soc. Psychol.* 61, 743–754

48 Alibali, M., Flevares, L. and Goldin-Meadow, S. (1997) Assessing knowledge conveyed in gesture: do teachers have the upper hand? *J. Educ. Psychol.* 89, 183–193

49 Goldin-Meadow, S., Wein, D. and Chang, C. (1992) Assessing knowledge through gesture: using children's hands to read their minds *Cognit. Instruct.* 9, 201–219

50 McNeill, D., Cassell, J. and McCullough, K-E. (1994) Communicative effects of speech-mismatched gestures *Res. Lang. Soc. Interact.* 27, 223–237

51 Thompson, L.A. and Massaro, D.W. (1994) Children's integration of speech and pointing gestures *J. Exp. Child Psychol.* 57, 327–354

52 Kelly, S. and Church, R.B. (1997) Can children detect conceptual information conveyed through other children's non-verbal behaviors? *Cognit. Instruct.* 15, 107–134

53 Goldin-Meadow, S. and Sandhofer, C.M. (1999) Gesture conveys substantive information about a child's thoughts to ordinary listeners *Dev. Sci.* 2, 67–74

54 Rime, B. (1982) The elimination of visible behavior from social interactions: effects on verbal, nonverbal and interpersonal variables *Eur. J. Soc. Psychol.* 12, 113–129

55 Iverson, J.M. and Goldin-Meadow, S. (1998) Why people gesture as they speak *Nature* 396, 228

56 Rauscher, F.H., Krauss, R.M. and Chen, Y. (1996) Gesture, speech, and lexical access: the role of lexical movements in speech production *Psychol. Sci.* 70, 226–231

57 Alibali, M.W. and DiRusso, A.A. The function of gesture in learning to count: more than keeping track *Cognit. Dev.* (in press)

58 Goldin-Meadow, S. Giving the mind a hand: the role of gesture in cognitive change, in *Mechanisms of Cognitive Development: Behavioral and Neural Perspectives* (McClelland, J. and Siegler, R.S., eds), Erlbaum (in press)

59 Crowder, E.M. (1996) Gestures at work in sense-making science talk *J. Learn. Sci.* 5, 173–208