

ACQUISITION OF INTELLECTUAL AND PERCEPTUAL-MOTOR SKILLS

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■ **Abstract** Recent evidence indicates that intellectual and perceptual-motor skills are acquired in fundamentally similar ways. Transfer specificity, generativity, and the use of abstract rules and reflexlike productions are similar in the two skill domains; brain sites subserving thought processes and perceptual-motor processes are not as distinct as once thought; explicit and implicit knowledge characterize both kinds of skill; learning rates, training effects, and learning stages are remarkably similar for the two skill classes; and imagery, long thought to play a distinctive role in high-level thought, also plays a role in perceptual-motor learning and control. The conclusion that intellectual skills and perceptual-motor skills are psychologically more alike than different accords with the view that all knowledge is performatory.

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INTRODUCTION

This review is concerned with the similarities and differences between the acquisition of intellectual skills and the acquisition of perceptual-motor skills. The main question is whether the psychological mechanisms underlying the two forms of skills differ. If they do, the important question is why and how they differ. If they do not, the equally important question is why two such seemingly disparate skill domains are more alike than their surface features suggest.

The review is organized into three major sections. First, we define the terms in the title and review claims that acquisition of intellectual skills and perceptual-motor skills rely on different psychological mechanisms. Then we review evidence favoring the opposite viewpoint. Finally, we ask why the evidence supports the no-difference view so consistently.

Before proceeding, we wish to establish the limits of what is covered. Because of space limitations, the review must be selective. The discussion is restricted to one principal question: How “intellectual” are perceptual-motor skills? This question reflects our expertise (or lack of expertise in other areas) as well as our sense that recent work across a wide range of disciplines now provides evidence for the view that “skills of mind” and “skills of eye, ear, and muscle” are fundamentally similar.

A second limitation is that the tasks we discuss under the perceptual-motor heading and under the intellectual heading are diverse. More microscopic comparisons of tasks within these domains might reveal more subtle differences between them, but because the two classes of skill turn out to be fundamentally similar, this outcome obviates concern with more microscopic differences.

DEFINITIONS AND DISTINCTIONS

Definitions help. When we speak of a “skill” we mean an ability that allows a goal to be achieved within some domain with increasing likelihood as a result of practice. When we speak of “acquisition of skill” we refer to the attainment of those practice-related capabilities that contribute to the increased likelihood of goal achievement. By an “intellectual skill” we mean a skill whose goal is symbolic. By a “perceptual-motor skill” we mean a skill whose goal is nonsymbolic. Examples of intellectual skills are solving or making significant headway toward solving mathematics problems, and winning or at least competing respectably in chess. Examples of perceptual-motor skills are playing the violin so as to attract rather than repel one’s listeners, and boxing so as to repel rather than attract one’s opponents.

Intuitively, intellectual skills and perceptual-motor skills seem very different. Perceptual-motor skills seem more primitive than intellectual skills. Ontogenetically, perceptual-motor skills develop before intellectual skills, or at least before most intellectual skills are manifested. Phylogenetically, creatures “high on the

evolutionary ladder” are more obviously capable of intellectual skills than are creatures “lower down.”

Perceptual-motor skills also seem more tied to specific forms of expression. Being a chess player does not mean one can only play with pieces of a certain size, that one can only move pieces with one’s right hand, and so on. By contrast, being a violinist means one can play an instrument whose size occupies a fairly narrow range and that one must play with a rather rigid assignment of functions to effectors (bowing with the right hand, and fingering with the left). The seeming narrowness of perceptual-motor skill expression, contrasted with the seeming openness of intellectual skill expression, seems to follow from intellectual skills having symbolic outcomes and perceptual-motor skills having nonsymbolic outcomes. Symbolic outcomes need not be realized in specific ways and can rely on abstract rules. Nonsymbolic outcomes, by contrast, need more specific forms of realization and seem to depend on restricted associations between stimuli and responses.

Another difference between intellectual and perceptual-motor skills is that the two kinds of skill seem to be represented in different parts of the brain. For example, structures homologous to the optic tectum, a nucleus located on the dorsal surface of the midbrain, have a common function in all vertebrates—coordinating visual, auditory, and somatosensory information relevant to the control of orienting movements of the eyes, ears, and head (Stein & Meredith 1993). Similarities in structure and function between these and other brain areas associated with perceptual-motor behavior suggest that mechanisms for control of perceptual-motor skills are both highly specialized and conserved across species. In contrast, what distinguishes the human brain from the brains of other species (even closely related ones) is the differential growth of brain regions most strongly associated with intellectual skills, such as the association areas of the cerebral cortex (Allman 1999). That these areas serve intellectual functions is supported by a large clinical and experimental literature (Gazzaniga et al 1998). Together, these diverse sources of information suggest that perceptual-motor and intellectual skills depend on distinct brain circuits.

Another way in which intellectual and perceptual-motor skills seem to differ is that it is usually easier to articulate the knowledge that allows for performance of intellectual skill than to articulate the knowledge that allows for performance of perceptual-motor skills. Thus, one can write the steps needed to solve a mathematics or chess problem and expect others to solve the same or similar problems by consulting those instructions. By contrast, no one has ever managed to write the instructions for riding a bicycle or bouncing on a trampoline and then find the reader successfully engaging in these tasks based on reading alone. The only way to learn perceptual-motor skills, it is said, is to do them.

A final way in which intellectual and perceptual-motor skills are said to differ is that individual differences seem faithfully to reflect the division between the two skill types. Some gifted gymnasts are inarticulate, and some gifted orators are clumsy. Specialization of talent seems to reflect specialization of acquisition

mechanisms. The fact that talents seem to divide so easily between intellectual and perceptual-motor domains provides more fuel for the argument that the two kinds of skills are functionally far apart—as far apart, one might say, as gym lockers and libraries in a typical university.

QUESTIONING THE DISTINCTION

Having offered arguments for the proposition that there is a psychologically meaningful basis for the view that intellectual skills and perceptual-motor skills are fundamentally different, we consider arguments for the opposite view. We begin by re-examining some of the claims made in the previous section and then turn to other lines of evidence. This section is longer and more replete with references than the last, which hints at where we think most of the evidence lies.

Transfer Specificity

As mentioned above, one putative difference between intellectual and perceptual-motor skills is that perceptual-motor skills seem more specific than intellectual skills. There are two reasons to question this proposal. One pertains to transfer specificity. The other pertains to perceptual-motor generativity.

Both perceptual-motor and intellectual skills are typically characterized by specificity of transfer. Practiced skills generally carry over only narrowly to similar contents and contexts. This phenomenon forms the basis for the identical elements theory of Thorndike (1903; see Hilgard and Bower 1975 for discussion). The main idea in identical elements theory is that transfer depends on having shared elements in acquisition and transfer; the larger the number of such shared elements, the greater the likelihood that transfer will occur. Singley & Anderson (1989) updated Thorndike's identical elements theory by suggesting that the relevant elements are production rules that apply both in acquisition and in new situations. Other versions of identical elements theory have been discussed by MacKay (1982), Kramer et al (1990), and Rickard & Bourne (1996). None of these theorists emphasizes a split between symbolic and nonsymbolic elements. Rather, all of them allow elements to be abstract in the sense that they pertain to whatever declarative or procedural knowledge is relevant for the task at hand. From the perspective of identical elements theory, there is no reason to expect transfer to be more limited for perceptual-motor skills than for intellectual skills, or vice versa, and the literature supports this expectation.

A particularly striking phenomenon is transfer asymmetry—the failure of transfer between different uses of what appears to be the same underlying knowledge. For example, McKendree & Anderson (1987) demonstrated failure of transfer between practice in generating and evaluating functions of the LISP programming language. Similarly, Fendrich et al (1993) found only partial transfer between items as similar as reversed multiplication facts (e.g. 3×4 and 4×3). Transfer asymmetry has also been demonstrated in the perceptual-motor domain (for review, see

Schmidt & Lee 1999, pp. 318–21). For example, Proteau et al (1992) showed that performance in a manual aiming task (hitting a target as quickly and accurately as possible) was impaired by letting participants see what they were doing if they had previously practiced the task without visual feedback. Usually manual aiming is aided by visual feedback, which makes it remarkable that supplying visual feedback late in training hurts performance. The fact that specificity of transfer is not markedly different within intellectual or perceptual-motor skill domains has been underscored in a volume edited by Healy & Bourne (1995).

Perceptual-Motor Generativity

Another reason to question the claim that perceptual-motor skills are more specific than intellectual skills is that perceptual-motor skills are more generative than often assumed. The hallmark of generativity in intellectual performance is, of course, the endless novelty of language. Perceptual-motor skills may seem, by contrast, to be less creative, but as more research has been done on perceptual-motor skill acquisition, a richer appreciation has developed of the endless novelty of physical action.

Consider the fact that any healthy person who can write with the preferred hand can also write with the nonpreferred hand. Written output from the nonpreferred hand preserves most of the spatial characteristics of written output from the preferred hand, and though writing with the nonpreferred hand is less fluent at first, with practice it becomes more so (Newell & van Emmerick, 1989). A challenge for motor control research has been to explain how it is possible to generate what is essentially the same written output with virtually any part of one's body—for example, even when the pen is held between one's toes or teeth.

Recent computer simulations have shown that writing with any part of the body can be achieved by guiding the pen through series of spatial and postural positions specified by a visuo-spatial representation of desired written output (Meulenbroek et al 1996). This method allows the same written output to be generated with different body parts. Other perceptual-motor achievements that may be taken for granted, such as reaching around obstacles to take hold of desired objects, rely on equally sophisticated computational and representational capabilities (Rosenbaum et al 1999).

Abstract Rules Versus Reflexlike Productions

As stated above, intellectual skills seem to rely on abstract rules more than do perceptual-motor skills. How well does this contrast stand up to scrutiny?

Contrary to the hypothesis, some intellectual skills seem to be represented by highly specific associations. Logan (1988), for instance, in his instance theory of automaticity, argued that intellectual skills such as arithmetic may be acquired as specific episodes involving particular answers to particular problems. Artificial grammar learning may likewise depend on the learning of specific features or chunks of grammatical strings rather than abstract rules (Dulany et al 1984). There

is debate about the extent to which intellectual skills depend on instances rather than rules, but it is almost certainly incorrect to say that intellectual skills rely only on abstract rules.

Similarly, it is almost certainly incorrect to say that perceptual-motor skills rely only on learned instances (i.e. simple reflexlike productions). This is illustrated by Koh & Meyer's (1991) finding that subjects can induce functions relating continuous stimulus dimensions (e.g. the length of a seen line) to continuous response dimensions (e.g. the duration of a button press). When subjects in Koh & Meyer's experiment were presented with new line lengths, their response durations indicated that they had induced the function relating line length to duration.

Other perceptual-motor skills seem to manifest function learning as well. Examples are prism adaptation (see Redding & Wallace 1997, for review), haptic exploration (Turvey 1996), and adaptation of limb movements to force perturbations (Condit et al 1997).

Neural Substrates

As noted above, another supposed difference between intellectual and perceptual-motor skills is that the two kinds of skill are subserved by different brain areas. However, this view has been challenged by recent findings concerning the motor cortex and cerebellum.

The traditional view of the cerebellum is that it contributes primarily to the coordination and control of movement. Damage to the cerebellum often results in distinctive motor symptoms, such as reduced muscle tone, delayed movement initiation, motor planning errors, and tremor (Holmes 1939). However, since the mid-1980s substantial evidence has also accumulated that the cerebellum serves a number of cognitive functions (Fiez 1996, Leiner et al 1995). Clinical studies have suggested that cerebellar damage is associated with deficits in conditioning (Bracke-Tolkmitt et al 1989) as well as the analysis of temporal duration (Ivry & Keele 1989). Neurological studies of children with developmental disorders have linked disturbances in the cerebellum to autism (Courchesne et al 1987) and Williams' syndrome (Rae et al 1998). Brain imaging research has shown that the cerebellum is active during performance of tasks as varied as word generation (Petersen et al 1989), sequence learning (Jenkins et al 1994), tactile discrimination (Gao et al 1996), and maintenance of information in working memory (Desmond et al 1997). Thus, an emerging view of the cerebellum is that it plays a role in intellectual as well as perceptual-motor performance (Leiner et al 1995). A general hypothesis about the cerebellum that may provide a unified account of its role is that it contributes to the prediction and preparation of sequences (Courchesne & Allen 1997). Insofar as sequences can consist of symbols (the *sine qua non* of intellectual skills) or stimuli and response (the *sine qua non* of perceptual-motor skills), the cerebellum need not be viewed as a purely perceptual-motor organ nor as a purely intellectual organ. The distinction between intellectual and perceptual-motor skills is not one that the cerebellum respects.

With regard to the motor cortex, the classical view is that this site is little more than a “launch pad” for movements (see Evarts 1981, for review). However, this view has undergone considerable revision. In one well-known study, Georgopoulos et al (1989), recorded from cells in the motor cortex of a monkey that saw a light and then had to direct its hand to a target 45° away. The composite activity of the cells could be represented as a “population vector” with a magnitude and direction closely related to the monkey’s hand movement. Georgopoulos et al found that the direction of the motor cortical population vector “rotated” between the time the monkey first saw the light and the time it began directing its hand to the angularly displaced target. This outcome suggests that the motor cortex is involved in a higher level of planning than would be expected if it merely received and relayed signals from higher centers at the moment movement is due.

Explicit Versus Implicit Knowledge

Another difference between intellectual and perceptual-motor skills mentioned above is that perceptual-motor skills are generally harder to articulate than intellectual skills. Implicit knowledge seems more naturally linked to perceptual-motor skills than to intellectual skills, whereas explicit knowledge seems more naturally linked to intellectual skills than to perceptual-motor skills.

How meaningful are these links? Not very, in our opinion. Certainly, perceptual-motor skills are often acquired without an accompanying ability to articulate rules governing performance. For example, Pew (1974) reported that participants learning to track a moving spot on a computer screen got better and better on the middle portion if it was repeated, though they indicated that they did not notice the repetition. Similarly, nonverbal creatures (animals and preverbal children) can acquire perceptual-motor skills without the symbolic skills to represent and report the corresponding rules. Thus, perceptual-motor skills can be learned implicitly, as suggested earlier.

But can intellectual skills also be learned implicitly, contrary to what was said before? There is evidence that they can be. Repeated sequences of stimuli (lights) and responses (keypresses) in reaction time tasks can be learned without easily verbalizable knowledge of the repetitions (Nissen & Bullemer 1987; but see Shanks & Johnstone 1999). As in the study of Pew (1974), performance improves on repeated sequences even when subjects do not report explicit knowledge of the repetitions (see Goschke 1998, for review).

One might say that serial reaction-time tasks are not “intellectual enough” to shed light on tasks that are unambiguously intellectual. There is evidence, however, that both mathematical problem solving and artificial grammars are learnable on the basis of rules or regularities that are not verbally represented as such. Acquisition of arithmetic problem-solving skills with complex goal structures shows a benefit of consistent goal structures even though subjects are poor at reporting those goal structures (Wenger & Carlson 1996). Similarly, learning of artificial verbal grammars does not depend on the ability to articulate the rules

defining the grammars (see Reber 1992, for review). Finally, speakers of natural languages cannot articulate rules for generating or comprehending grammatical sentences; if they could, theoretical linguistics would be easier. In general, the available evidence indicates that intellectual skills need not depend on the deliberate application of rules in verbal or other symbolic formats.

A caveat is in order here. It must be admitted that the empirical and theoretical status of implicit learning of intellectual skills remains controversial (e.g. Carlson 1997, Dienes & Perner 1999, Shanks & St. John 1994). Assessing explicit knowledge poses methodological difficulties (Perruchet et al 1990, Shanks & Johnstone 1999), and for many tasks competing accounts suggest alternative ways in which the knowledge underlying intellectual skill might be divided between declarative and procedural components (Redington & Chater 1996, Servan-Schreiber & Anderson 1990). Explicit declarative knowledge of facts is often, though not always, accompanied by awareness of what has been learned as well as the circumstances of learning, in contrast to typical instances of perceptual-motor learning. Still, intellectual and perceptual-motor skill acquisition cannot be generally distinguished on the basis that one is explicit and the other is implicit. Neither category of skill learning is necessarily accompanied by the ability to articulate the rules governing observed performance.

Individual Differences

The previous list of putative differences between perceptual-motor skills and intellectual skills included individual differences. The fact that some people are talented in perceptual-motor domains or in intellectual domains suggests a rift between the two skill areas.

Two responses can be given to this argument. The first is that individual differences in the expression of a skill do not necessarily bear on the capacity for acquisition of the skill. An actor with a beautiful speaking voice, for example, may not necessarily be able to learn his or her lines more easily than an actor with a raspy voice. Second, the question of how and whether skill competencies should be partitioned is an old but still unresolved issue (see, for example, Gardner 1983).

Regarding the partitioning of intellectual and perceptual-motor skills, it is striking that correlations between performance levels within some domains are as low, or nearly as low, as the correlations one would expect for wholly unrelated realms of performance. For example, the correlation between the time to maintain balance on a seesaw or on a freely standing ladder is less than 0.25 (Bachman 1961). Obtaining such a small value violates what one would expect if one thought there were a general "balancing ability." In general, correlations over participants between different perceptual-motor tasks rarely exceed 0.40 (see Schmidt & Lee 1999, for review). The low correlations between perceptual-motor tasks weaken the hypothesis that perceptual-motor skills comprise some set of abilities that can be isolated from intellectual skills on the basis of high inter-correlations.

Learning Rates

If perceptual-motor skills and intellectual skills were acquired in fundamentally different ways, one would not necessarily expect the time course of their acquisition to be the same. In fact, charts of progress over time in the two skill domains are remarkably similar. As observed by Crossman (1959), the time to complete a task diminishes with practice at a lower and lower rate as practice continues. One way to capture this relation is with a power function, $T = aP^{-b}$, relating the time, T , to complete the task to the number of trials, P , that the task has been practiced; where a and b are nonnegative constants. Debate has arisen about whether the power function is the best formula for relating T to P (Heathcote et al 2000), but the tendency for performance time to decrease at ever lower rates is well established.

The feature of practice-related speeding of performance that is of greatest importance for present purposes is that the way performance speeds with practice is the same in perceptual-motor domains and in intellectual domains. Thus, in addition to the task studied by Crossman (1959)—cigar rolling—the relation holds for the time to draw figures with sight of the drawing hand restricted to a mirror (Snoddy 1926), the time to edit text with a computerized word processor (Singley & Anderson 1989), the time to prove theorems in a geometrylike system (Neves & Anderson 1981), and even for the time for the prolific author Isaac Asimov to write books (Ohlsson 1992).

What mechanisms allow the time on a task to decrease with practice by smaller and smaller amounts as practice continues? One answer can be based on Bryan & Harter's (1897) classic model of chunking. Skill acquisition entails formation of procedures at successively higher levels. The higher the level of the procedure, the longer it takes to learn it, so the longer it takes to see a corresponding reduction in the task completion time. Consistent with this explanation, and consistent with the view that intellectual and perceptual-motor skills are formed through similar means, the timing of successive responses in perceptual-motor tasks as well as intellectual tasks both reveal hierarchical "unpacking" of chunks of knowledge. Thus, skilled chess players returning pieces from a game onto a board return the pieces in bursts separated by longer lags. The long and short time intervals are related, respectively, to inter- and intrachunk boundaries (Chase & Simon 1973). Similar timing results are found in recall of semantically organized word lists (Reitman & Rueter 1980) and production of rapid finger-tapping sequences (Povel & Collard 1982, Rosenbaum et al 1983).

Training Effects

Many similarities have been observed between the effects of different training regimens on the learning of perceptual-motor and intellectual skills (Schmidt & Bjork 1992). Massed practice produces better immediate performance than spaced practice, both in verbal learning (e.g. Glenberg 1977a) and in motor learning (e.g. Shea & Morgan 1979), and random or spaced practice leads to better

long-term retention than does blocked or massed practice in both domains. Relevant evidence is reviewed for perceptual-motor skill in Magill & Hall (1990), and for intellectual skill in Melton (1970), Landauer & Bjork (1978), and Rea & Modigliani (1985).

Perceptual-motor and intellectual learning are also affected in similar ways by variations in feedback frequency. As reviewed by Schmidt & Bjork (1992), providing frequent feedback to subjects learning a motor task such as rapid serial arm positioning leads to good short-term retention but poor long-term retention, whereas providing infrequent feedback leads to good long-term retention but poor short-term retention (Schmidt et al 1989, Winstein & Schmidt 1990, Wulf & Schmidt 1989). Comparable results have been obtained for acquisition of verbal paired associates (Krumboltz & Weisman 1962, Schulz & Runquist 1960) and computer languages (Schooler & Anderson 1990).

Yet another way in which motor and verbal learning show similar training-related effects pertains to the consequences of exposing subjects to the same or different materials during training. Using the same materials (constant training) leads to better performance just after training but worse performance in later tests. By contrast, exposing learners to different materials (variable training) leads to worse performance just after training but better performance in later tests. The long-term benefit of variable training is observed with perceptual-motor tasks such as pressing a button when a moving object reaches a target or tossing a bean bag into a bin (see Shapiro & Schmidt 1982, for review). The long-term benefit of variable training is also observed with intellectual tasks such as learning new words for familiar concepts (see Bransford et al 1977).

Learning Stages

As might be expected from the foregoing, long-term learning of intellectual and perceptual-motor skills appears to go through similar stages. The classical view of skill acquisition proposed by Fitts (1964) to account for perceptual-motor skill acquisition has been extended to the acquisition of intellectual skills, most notably by Anderson and colleagues (Anderson 1982). Fitts proposed that there is a declarative stage in which the basic rules of a task are learned and, if necessary, articulated. Then there is an associative stage in which the procedures of the task become more fluent. Finally, there is an autonomous stage in which the procedures become more automatic, being performed more rapidly and with greater immunity to disruption from outside events. Anderson (1982) showed that this stage description applies to intellectual skills as well as perceptual-motor skills.

Imagery

A hallmark of intellectual skill is the capacity for imagery. Albert Einstein claimed that images came to him before equations, and others have also reported that imagery played a major role in their thinking. Insofar as imagery plays such a prominent role in thinking, one might expect it to play little or no role in

perceptual-motor skill and to be scarcely influenced by ongoing perceptual-motor activity. Neither of these expectations is borne out, however.

That imagery plays a role in perceptual-motor skill has been shown in many studies (see Crammond 1997, Jeannerod 1994, for review). Imaging one's own body movements "lights up" many of the same brain areas as actual performance of those movements (Roland 1993). Mental simulation of perceptual-motor tasks also takes about as long as actual performance of those tasks, and this is true for tasks as varied as walking (Decety & Jeannerod 1995), writing (Decety et al 1989), pointing (Sirigu et al 1996), speaking (MacKay 1982), and grasping (Johnson 2000). When people are asked to imagine performing movements in time with a metronome, the pace at which they report imagined breakdowns of performance corresponds to the frequencies at which the same tasks break down when they are actually performed (Sirigu et al 1996).

Whereas the studies just mentioned concern imagery of one's own movements, other studies have explored the possibility that imagery for events in the external environment is affected by ongoing perceptual-motor activity. Wohlschläger & Wohlschläger (1998) and Wexler et al (1998) found that mental rotation is affected by manual rotation. If the hand turns in the same direction as a mentally rotated object, the mental rotation speed is higher than if the mental and manual rotations go in opposite directions. This outcome suggests that visual imagery and the control of perceptual-motor tasks rely on common mechanisms. Direct physiological support for this conclusion was mentioned above in connection with the monkey mental rotation study of Georgopoulos et al (1989).

CONCLUDING REMARKS

In this review we have asked whether the acquisition of intellectual skills and the acquisition of perceptual-motor skills rely on similar or different psychological mechanisms. Our conclusion is that though the two kinds of skills may be distinct in their forms of expression, their means of acquisition are strikingly similar. In the remainder of this article we ask why the evidence leads to this conclusion.

Possible Reasons for the Similarities

One reason may be rooted in development. Perceptual-motor skills and intellectual skills have closely related developmental origins, as observed by Piaget (1954). Piaget's description of early development associates the development of thought with the emergence of skilled action. For example, the achievement of object permanence is based, according to Piaget, on the infant's realization that the identity and persistence of objects is independent of one's own behavior.

This view has been amplified and extended by others. For example, Diamond (1990) argued that the achievement of object permanence requires both the development of memory and the emergence of mechanisms for inhibiting inappropriate

responses, such as reaching to a location where an object recently was but no longer is. Diamond associated the development of object permanence with the maturation of circuits in prefrontal regions of the cerebral cortex. Diamond's neurological perspective illustrates the close, perhaps inseparable, links between intellectual and perceptual-motor substrates of a wide range of concepts.

In a similar vein, Smith et al (1999) argued that puzzling aspects of infants' behavior in a classic object permanence task (the A-not-B task) may reflect infants' inability to successfully coordinate looking and manual reaching motions and memories of past actions. Smith et al's (1999) argument challenges the notion that during development intellectual skills can be usefully separated from their perceptual-motor realizations.

Another reason to believe in the fundamental similarity of the acquisition of intellectual and perceptual-motor skills is the growing popularity of the hypothesis that all intellectual skills are performatory—that is, that all skills are grounded in and supported by perceptual-motor activity, even at high levels. Piaget (1954), as noted earlier, suggested that mental operations and the intellectual achievements they support originate in interiorized action (see Chapman 1988); Bartlett (1932, 1958) argued that thinking is a skill (see Johnson-Laird 1982 for discussion); Weimer (1977) advocated a motor theory of mind, emphasizing the role of perceptual-motor activity in cognition; Kolers (Kolers & Roediger 1984) promoted a “proceduralist” view of memory and cognition, and Neisser (1983) endorsed a similar view, motivated by ecological considerations. Glenberg (1997b) discussed the role of perceptual-motor activity in memory processes, and Barsalou (1999) argued that all symbolic representation may be based in perception. One of the present authors offered a similar argument in the context of a theory of consciousness and cognitive skill (Carlson 1997). A class of findings that supports the view that intellectual skills are performatory is that coordination and timing seem to be required for intellectual as well as perceptual-motor skills. Mental skills in a number of domains depend on the use of the external environment to maintain information for immediate performance, requiring real-time coordination of mental activity with externally available information (Ballard et al 1995, Cary & Carlson 1999, Larkin 1989, Zhang & Norman 1994). Similarly, performatory properties of speech affect the capacity and other properties of short-term memory for verbal materials (Cowan et al 1997; Zhang & Simon 1985). Finally, as with perceptual-motor skills, practicing intellectual skills results in establishing appropriate timing and coordination of component subskills (Cary & Carlson 1999, Wenger & Carlson 1995, Yee et al 1991). Thus, coordination, which has long been viewed as crucial for skills of perception and movement, turns out to be needed as well for skills of the intellect (Neisser 1983).

A final reason why the evidence points to a basic similarity of intellectual and perceptual-motor skill acquisition is that across animal species, the complexity of observed perceptual-motor skills is correlated with the complexity of intellectual skills. Complex nonverbal skills, such as manufacture of multi-component tools, only occur in humans. Recognition of this relation has prompted the hypothesis that

the evolution of brain areas credited with the development of language (e.g. Broca's area) may have paved the way for complex behavioral sequencing (Greenfield 1991, Calvin 1994; Keele, interviewed in Gazzaniga et al 1998, pp. 398–99).

What's the Difference?

Having argued for the view that intellectual and perceptual-motor skills are acquired in similar ways, we need to dispel the impression that we think there is no difference between the two kinds of skill. Clearly, there is something special about intellectual function. But what is the difference?

Intellectual skills, as indicated in our definition of the term, have symbolic outcomes. They consist of actions that relate not just to the here and now but also to events that may be remote in time or space. Perceptual-motor skills, by contrast, have nonsymbolic outcomes and consist (or seem to consist) of actions that relate only to the immediate time and place in which they occur. What distinguishes intellectual skills from perceptual-motor skills then is the remoteness of the events to which they relate. This suggests that intellectual and perceptual-motor skills differ in degree rather than in kind, which may be why their means of acquisition seem so similar.

How remote are the events to which perceptual-motor activities relate? Granting that intellectual skills, expressed in such forms as writing science fiction, can relate to events infinitely far away in time and location, are perceptual-motor skills exclusively related to the place and time in which they are situated? Addressing this question provides a final clue about the similarities between perceptual-motor and intellectual skill acquisition. A great deal of research in the area of perceptual-motor control has shown that the genesis of voluntary action is accompanied by anticipation of future events. The time to initiate a sequence of motor responses increases with the length of the forthcoming sequence (Rosenbaum 1987, Sternberg et al 1978); errors in performance suggest that behavioral plans contain considerable structure (Dell 1986, Lashley 1951, Norman 1981); latencies of different types of responses to different types of stimuli suggest that perceptual consequences of forthcoming acts are represented in advance (Greenwald 1970, Hommel 1996); and action choices made early in behavioral sequences reflect anticipation of later behavioral states (Rosenbaum et al 1993). These findings indicate that action plans project into the future. This body of research has also shown that low-level features of performance have relatively short spans, whereas high-level features have longer spans, some extending to months (e.g. animal migration).

Considering the long time scales over which purposeful action can occur, one must again question the meaningfulness of the distinction between perceptual-motor skills and intellectual skills. If bees can communicate the whereabouts of recently visited flowers, it is unclear why, except for the fact that bees aren't human, this behavior should not be viewed as an intellectual skill.

What this leads to is the realization that perceptual-motor skills are no less intelligent than intellectual skills. The fact that modern technology has enabled

computers to beat the world's greatest chess master (*Newsweek* May 5, 1997), but has not yet enabled robots to climb trees as well as five-year-olds or pick strawberries as well as farm workers attests to the fact that our understanding of the psychological substrates of perceptual-motor skill is still primitive compared to what we know about intellectual skills. We have verbal intelligence that makes it easier for us to describe verbal intelligence than to describe nonverbal intelligence, but we must be careful not to conclude from this that perceptual-motor skills are inferior to their intellectual counterparts.

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