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Studying human expertise: Beyond the binary paradigm

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Abstract. The empirical study of human expertise has grown up largely within the information-processing framework. We contend that assumptions and practices inherited from that framework have significantly hampered the study of expertise. Most studies have been conducted within a binary paradigm that sets novices apart from experts while ignoring any qualitative distinctions in between. End-state description has been preferred over accounts of learning; accounts of learning as a smoothly continuous process have been preferred over accounts of qualitative change. To overcome the binary paradigm, psychologists need to adopt an explicitly developmental approach, one that identifies multiple way stations toward expertise and seeks to explain qualitative changes in knowledge and motivation. We consider two insufficiently developmental conceptions ('theory-change' accounts and global stage models) and two others that, in our view, harbour greater promise (the Piagetian framework as elaborated by Feldman and the Vygotskian framework as extended by Scribner). Progress in the study of human expertise doesn't just depend on the more widespread adoption of developmental research programmes. There also needs to be more open and frank discussion of the strengths and weaknesses of different frameworks than has been customary.

1. Expertise and information processing psychology

Over the past quarter century, the study of human expertise has burgeoned. It is now an entrenched specialty within cognitive science. As empirical studies have proliferated, the vast majority of them dependent on information-processing (IP) models of human cognition, certain strategies of empirical research and modes of explanation have become habitual. We are concerned that these strategies and modes of explanation, valuable as they were in launching the field, now constitute an impediment to further growth in psychologists' knowledge of expertise. Specifically, they impede our understanding of the processes by which expertise develops.

We describe alternative research strategies that we believe are able to do justice to the developmental questions. Some developmental conceptions, such as the 'theory-change' approach and global stage models of expertise, are radically incomplete; they offer some insights but in the end are inadequate to account for the acquisition of expertise. Updated Piagetian and Vygotskian approaches are more powerful and harbour greater promise. We don't expect these developmental approaches to go unchallenged; none of them claims to answer all the questions, and the assumptions they make are often sharply at variance with those that prevail in IP and AI. We would like to spark some public discussion about the merits of developmental versus IP approaches to human expertise; at present, there is scarcely any.

In this article, we draw many of our examples from computer programming. Maybe we are simply appealing to convenience, as some of our own empirical studies have been in this field. All that matters for our current purposes is that computer programming contains several rich domains of expertise, and that empirical studies have been going on long enough in this field to let us assess what conventional approaches have taught us and what remains inaccessible to them.

Empirical work on expertise in computer programming began in the mid-1970s (Brooks 1977, Sheil 1981, Shneiderman 1980). The usual goal of such research has been to exhibit differences between a group of novice programmers and a group of expert programmers. Some typical findings: expert programmers are better than novices at recalling meaningful (but not scrambled) ALGOL programs (McKeithen *et al.* 1981); they are better at finding bugs, particularly those that depend on a high-level representation of the programs they read (Gould 1975, Adelson 1984); and they are more likely than novices to use standard programming plans (Soloway and Ehrlich 1984). In a rather unusual piece of research that approached acquisition more systematically and sought a process explanation, the transition from novice to expert was taken to consist in the acquisition of a body of syntactic rules, chartable using the Power Law of Practice (Anderson *et al.* 1989).

2. The binary paradigm

All of these empirical studies have operated within the confines of the *binary paradigm* (Campbell *et al.* 1992). Work within this paradigm presumes that:

(1) Novice – expert is a binary distinction.
(2) Novice knowledge and expert knowledge can be compared statically.
(3) Experts are people with a certain amount of experience, rather than people who satisfy specific criteria of knowledge or skill.

A few thoughts about the range of computer programming ability to be found in the real world instantly cast doubt on the first and third assumptions. Can we do justice to the full spectrum of skill and the long, hard path to its acquisition when we try to describe it all with two categories? If an 'expert' in one study has passed several programming courses and an 'expert' in another is a professional at the top of her field, what do they have in common?

Those who imposed the binary paradigm on expertise in programming did not lack for models. The classic studies of expertise in the IP framework, such as Chase and Simon's (1973) examination of memory for chess positions, or Chi *et al.*'s (1981) treatment of problem categorizations in Newtonian mechanics by students and instructors, relied on the binary categorization already mentioned. They did this even though some IP researchers insisted, quite early on, that true expertise takes at least 10 years to acquire (Chase and Simon 1973, Ericsson *et al.* 1993). Moreover, the classic IP studies concentrated on describing the 'expert' end state rather than the process of acquiring expert knowledge or the way stations along the path toward expertise.

3. The commitment to end state description

The preference for describing the end state is not an accidental quirk. It is symptomatic of choices made during the early days of IP research:

> Our emphasis on performance ... represents a scientific bet ... we have too imperfect a view of the system's final nature to be able to make predictions from the developmental process to the characteristics of the structure it produces ...
>
> If performance is not well understood, it is somewhat premature to study learning. Nonetheless, we pay a price for the omission of learning, for we might otherwise draw inferences about the performance system from the fact that the system must be capable of modification through learning. (Newell and Simon 1972, pp. 7–8)

It is not surprising, then, that Glaser's (1989) latter-day summary of what IP studies have taught us about expertise emphasizes 'components of competent[1] performance': the manner in which expert knowledge is structured; the manner in which problems are categorized; a move from declarative to 'compiled' procedural knowledge and from controlled to automatic processing; metacognitive skills; and theory or schema change.[2] 'As learning theorists ... we appear to be at the novice stage of less than integrated bundles of knowledge ... On the other hand, the picture of the goal states of competence is rich' (Glaser 1989, pp. 278–279).

4. Inadequate accounts of acquisition

Even those IP efforts that pay heed to the process of acquisition are hemmed in by theoretical preoccupations. The lesson that Ericsson and Staszewski (1989) and Staszewski (1988) wish to draw from a landmark longitudinal study of mental calculation is that acquiring expertise means acquiring skills for managing one's working memory. That experts in mental multiplication (or in some other areas, like keeping track of diners' orders in a busy restaurant) need such skills we do not doubt. It remains to be seen what role working memory management plays in such expert accomplishments as recognizing that a Smalltalk program is inelegant and unmaintainable (Campbell *et al.* 1992) or sensing that all firefighters must vacate the building immediately because the floor is about to fall in (Klein *et al.* 1989).

In another exhibition of theoretical preoccupation that has now become textbook material, Anderson *et al.* (1989) and Anderson (1995) set out to reduce progress toward expertise to such operations as chunking, compilation of declarative knowledge into procedures, and the Power Law of Practice. Another researcher has gone so far as to fit a power function to changes over time in the rating points of tournament chess players (Charness 1989). Such explanations assume that 'practice makes perfect' (Cooke 1990)—or, at least, that deliberate practice does (Ericsson *et al.* 1993). And they simply can't account for qualitative change, or new knowledge.

Chunking depends on the production rules already built into the system, and the pre-existing symbols in which their conditions are stated. The Power Law of Practice applies whenever some dimension of performance can be charted on a continuous scale of measurement over time. When speed is that dimension, the Power Law is a mathematical description of speedier execution with practice—speedier execution of *the same skills*. It can't explain how previously acquired skills are modified, or new skills are acquired. IP accounts of automaticity imply that what becomes automatic is virtually the same as it was before; the only important difference is that it no longer requires conscious attention for its execution.

What really happens when children get better at answering questions like 'What is 5+4?'? A fifth-grader doesn't just answer the questions faster, more smoothly, and more 'automatically' than a first-grader; the fifth grader uses different mental processes. Where the first-grader has to carry out the addition again, using a counting-based strategy, the fifth-grader retrieves the answer straight from long-term memory

(Ashcraft 1992). In general, when people get more 'automatic' in their processing there is every reason to suppose that they are really mastering new skills (Spelke *et al.* 1976). Severally or jointly, mechanisms like chunking and the Power Law of Practice can't explain how development occurs (Campbell and Bickhard 1992, Bickhard and Terveen 1995, Bickhard and Campbell 1996).

At their best, such accounts of learning as can be had in IP theory simply don't cover common happenings in becoming an expert, such as the formation of new goals (Neches *et al.* 1987, pp. 32–34). They can't account for the emergence of esthetic criteria as a critical part of one's work. Nor can they account for changes of meaning: commonplace statements about the language that Smalltalk programmers are exposed to early in their training (for instance, 'Everything is done by sending a message to an object') get revisited and reinterpreted at higher levels of expertise (Campbell *et al.* 1992).

While IP treatments can't explain many kinds of learning, they can't explain any kind of metacognition. Knowing about knowing, metacognition, or what Piaget (1977) called 'reflective abstraction' may well be involved in the acquisition and extension of expertise (for two modest examples of this involvement, see Di Bello 1996 and Mathews *et al.* 1996). Information-processing psychologists talk about metacognition a lot; on occasion they encourage students to do it (Chi *et al.* 1989). Yet no existing variant of IP, not even the supposedly 'reflective' SOAR (Newell, 1990), allows for the possibility of knowing about knowing, let alone explains how it comes about (Campbell and Bickhard 1986, Bickhard and Terveen 1995).

IP accounts of expertise, then, have provided valuable descriptions of end states that cover certain kinds of expert knowledge, such as problem categories, significant configurations of chess pieces, or strategies for managing working memory. Meanwhile they have entirely ignored other significant aspects of expert knowledge, such as goals and esthetic criteria. And they have barely undertaken to explain how any of them are acquired.

5. Developmental alternatives

Both anecdotal accounts and a number of qualitative studies show that expertise develops: human beings move towards a flexible, adaptive understanding of a complex domain along a trajectory that is predictable, orderly, and invariant. Intermediate steps towards mastery (including their characteristic errors and limitations) seem unavoidable, even to those who are aware of their existence and might be motivated to avoid them. Even studies within the IP tradition have sometimes revealed these intermediate steps. For instance, Lesgold *et al.* (1988) found that fourth-year resident radiologists interpret some X-ray photographs less accurately than first-year radiologists; more expert radiologists cease committing these errors. Needless to say, what developmental psychologists call a 'growth error' resists explanation via proceduralization of pre-existing declarative knowledge or the Power Law of Practice; in order to make sense of their findings, Lesgold *et al.* were compelled to turn to developmental accounts like those of Karmiloff-Smith (1986), and offshoots of their work have taken an explicitly constructivist turn (Spiro *et al.* 1988).[3]

Developmental approaches are concerned with the emergence of knowledge rather than isolated end states. They ought to be more suitable, not only for describing expertise more deeply, but also for explaining how it comes about. Indeed, once attained, expertise doesn't stay put; real experts have ways of maintaining and improving their expertise. Acquiring expertise means acquiring ways of becoming *more* expert (Bereiter and Scardamalia 1993, Spiro *et al.* 1988).

Development is no simple phenomenon; there are more and less successful ways of trying to understand it. We begin by examining two developmental conceptions that produce less than they promise.

5.1. *'Theory-change' accounts*

Some psychologists (e.g. Vosniadou and Brewer 1987) have actually claimed that cognitive development is best understood as a 'novice–expert shift'. Such assertions presume that a lot is known about the acquisition of human expertise, when in fact the available evidence is skewed and fragmentary and the explanations leave much to be desired. And as the phrase 'novice–expert shift' indicates, they presume the adequacy of the binary paradigm.

The researchers who make these assertions are affiliated with what we might call the 'theory-change' school. They regard mental representations as theories and cognitive development as a process analogous to theory change in the history of science. Thus diSessa (1983) and McCloskey (1983) have likened the replacement of 'naive' physics by textbook Newtonian mechanics to the historical process by which Aristotelian physics was displaced by Newtonian physics. According to Vosniadou and Brewer (1987), children recapitulate the historical sequence from thinking of the earth as flat and stationary to a conception of their home planet as spherical and rotating; likewise, they begin with a geocentric conception of the universe and later reject it in favour of a heliocentric solar system. Wiser and Carey (1983) have claimed that children's tendency to confuse heat and temperature has historical antecedents.

We don't question the heuristic value of such parallels. But in many an area of expertise, there are none to be found. What historical changes are being recapitulated when a bassoonist becomes a true expert in his craft, or when a computer progammer becomes proficient in using object-oriented techniques to create the desired arrangement of windows and menus on the screen?

Worse yet for the 'theory-change' conception, it relies on two frankly incompatible assumptions about development. On the one hand, 'radical conceptual change', as envisioned by philosophers of science like Kuhn (1962) and Lakatos (1978), is supposed to take place during the 'novice–expert shift'. On the other hand, Carey (1985) has asserted that inferential capabilities are fixed at birth, and that young children and adult scientists have exactly the same understanding of the 'logic of confirmation[4]. Smith *et al.* (1985) have proposed that every concept is built out of more primitive concepts, or 'components'. In their appeals to fixed inferential capabilities and to concepts as assemblages of primitives, they are in complete agreement with the anticonstructivist philosopher Jerry Fodor (1972, 1981), who has argued that novel concepts could never develop, while allowing no way for them to arise through evolution either (Campbell and Bickhard 1987, 1992, Bickhard 1991).

The 'theory-change' approach has never broken out of the binary paradigm. To make matters worse, it simultaneously affirms and denies qualitative change in development.

5.2. *Domain-general stages of expertise*

In popular thinking, developmental psychology is identified with 'stage theories' like Jean Piaget's. But there are developmentalists who deny the existence of stages, and there is a good deal more to theories like Piaget's or Vygotsky's than their stage claims.

Still, any conception that puts stages in between 'novice' and 'expert' would seem better equipped than conventional IP to describe the developmental trajectory of skill acquisition. And by now a number of accounts have described becoming an expert in terms of moving through stages. We will begin with a simple, domain-general treatment.

Hubert and Stuart Dreyfus (1986), in a critique of standard symbolic AI and expert systems, have contended that the path towards human expertise in any ill-structured domain moves through five stages. In ascending toward expertise, learners move from the conscious application of context-free rules to 'intuitive' situation recognition; they also acquire a personal involvement in their decisions. In greater detail, the stage sequence looks like this:

(1) *Novice*. Goes 'by the cookbook'. Has learned some context-free rules and facts, makes analytical decisions, and has a detached commitment to the outcomes of those decisions.
(2) *Advanced beginner*. Has begun to learn how to analyse situations. Still makes analytical decisions with detached commitment.
(3) *Competent*. Has a chosen perspective (based on explicit planning) and an involved commitment in the outcome of decisions, which nonetheless remain analytic. Does a lot of conscious 'problem-solving'.
(4) *Proficient*. Can recognize problems 'intuitively,' on the basis of holistic similarity recognition. Has an experienced, not consciously chosen perspective, and involved understanding, but detached deciding.
(5) *Expert*. Can recognize situations and the actions that they afford, and can make intuitive decisions. Has involved commitment throughout the decision process, and can deliberate (i.e. reflect on his intuitions).

The five-stage scheme has been applied to chess playing and flying fighter planes (Dreyfus and Dreyfus 1986). Benner (1984) gathered evidence about Intensive Care Unit nursing from interviews and participant observation, and found that the developmental path toward expertise in this domain was consistent with the scheme.

What's missing from the five-stage scheme is any conception of the processes responsible for development through the stages. Dreyfus and Dreyfus appeal to no mechanism stronger than the 'inductive' accumulation of experiences. Moreover, they expect the same sequence of levels to arise in the development of any form of expertise. We aren't casting doubt on the broader utility of some of their distinctions (for instance, between proficiency and true expertise). But we do wonder whether the path toward expertise in a given domain might not depend to some extent on what is being mastered (Feldman 1980; see Campbell and Bickhard 1992, for an argument that developmental sequences that come about through learning will normally vary from one domain to another).

We think the most promising programmes of empirical research on expertise come out of two established developmental conceptions—those of Jean Piaget and Lev Vygotsky. Both of these conceptions have had to be extended and modified to make them suitable for the study of human expertise.

5.3. *Piaget and Feldman*

Piaget's genetic epistemology in its original form had little to say about expertise. Piaget's paramount interest was in universal capabilities, those that every normal human being tends to develop without being taught. Indeed, Piaget avoided studying the process of instruction, or knowledge and skills that might be learned by instruction.[5]

Some years ago, David Feldman (1980, 1986, 1994a, 1994b) undertook to extend Piaget's theory to 'nonuniversal' development; the 'cultural', 'discipline-based', and 'idiosyncratic' areas of his continuum include the types of expertise that are deliberately taught.

Feldman and his students have sought a rich description of multiple steps toward expertise that depends on the specific domain being mastered. For instance, their study of learning to juggle (Walton *et al.* 1988) identified eight levels of juggling expertise and tracked students' attitudes and feelings during the transitions between levels. Feldman uses a variant of Piaget's (1985) equilibration to explain transitions between the levels; his procedure incorporates a fine-grained analysis of the progress of various 'elements' of skill from one stage to the next, and the emotions connected with stage transitions (for additional examples, see Feldman, 1994a, 1994b).

We have found Feldman's extended Piagetian approach useful in our own research on expertise (Campbell 1990, Campbell *et al.* 1992). We employed interviews and longitudinal 'tape diaries' to chart the progress of professional programmers who were transferring from conventional procedural programming to object-oriented programming (using the Smalltalk language and environment). The cognitive challenges are noteworthy, even for programmers who were genuine experts in their old programming areas. Although enthusiastic proponents of intelligent tutoring systems have sometimes made undocumented claims to the contrary (Carroll *et al.* 1990, Carroll and Rosson 1991), professional programmers need at least two years to reach true expertise in the Smalltalk world—when they attain it at all. Our description of the acquisition of expertise in Smalltalk includes seven stages:

(1) *Interacting with the visual interface.* Becoming familiar with the windows and menus of the standard Smalltalk environment.
(2) *Syntax rules and order of precedence.* Learning about types of messages and the standard symbology of the language.
(3) *Locating classes and methods.* Finding the fragments of code, already built in to the Smalltalk environment, that must be modified by the programmer to get particular results.
(4) *Class versus instance distinction.* Understanding and using the basic distinction between class and instance variables, and class and instance methods.
(5) *Model - Pane - Dispatcher.* Understanding and using `Model`, `Pane`, and `Dispatcher`, the complex of Smalltalk classes that controls the behaviour of windows and menus and their interactions with the user's input. Because Smalltalk is primarily in demand for rapid prototyping of user interfaces, technical proficiency in Smalltalk essentially means ease of manipulating and modifying `Model`, `Pane`, and `Dispatcher`.
(6) *Object-oriented design.* Thinking and designing in object-oriented terms, not in old, functional terms translated into Smalltalk code. From our standpoint (and most programmers') only Stage 6 qualifies as true expertise.
(7) *The 'grandmaster' level.* Object-oriented design no longer needs to be a conscious goal; it has become 'second nature' for the designer.

Many issues about the nature and pace of transition between these stages remain to be explored. We find the emergence of esthetic criteria at Stage 6 to be particularly important, and almost certainly generalizable to other domains of expertise. At Stage

5, programmers become technically proficient at accomplishing any particular user interface effect they might be interested in producing, but their solutions are often awkward and kludge-ridden. At Stage 6, the aesthetics of object-oriented design and matters of elegance and maintainability become paramount (Campbell *et al.* 1992).

Identifying stages in the acquisition of expertise requires close attention to the particulars of the domain and the experience of its practitioners (Feldman 1994a); it puts greater demands on the researcher than running another batch of studies in the binary paradigm. Nonetheless, the Piaget–Feldman approach is beginning to show up in the work of other research groups; for instance, Wiedenbeck and Scholtz (1996) have identified 6 stages in the transition from programming in Pascal to programming in the string-processing language Icon.

5.4. *Vygotsky and Scribner*

The developmental theories of Lev Vygotsky (1934/1987) are contemporaneous with Piaget's earlier work (interestingly, both conceptions substantially predate AI and the 'cognitive revolution' in American psychology). Although Vygotsky made proposals about developmental stages, they were less significant in the body of his work than stages were for Piaget, and they have figured less in subsequent elaborations and applications of his ideas. Conversely, the Vygotskian tradition harbours a much greater appreciation than was customary for Piaget of the ways in which the social arrangement of things and activities influences the development of cognitive skill, and it makes an appeal to processes of 'internalization' rather than equilibration.

Recent work on 'culture and cognition' has as a rule been strongly informed by Vygotskian ideas (Rogoff 1990, Shweder 1990, D'Andrade 1990, Wertsch 1985). One common theme in this work is that two skill domains we would normally think of as the same turn out to have quite separate identities within the same person, for instance 'school maths' and 'shopkeeper maths' (Beach 1990, Carraher *et al.* 1985). Not a comforting result for researchers who assume that domains can be defined in terms of 'formal' disciplines or fields of study—as earlier IP researchers usually assumed (Larkin 1981).

As with Piaget, however, Vygotskian conceptions have had to be extended and adapted to apply to the acquisition of expertise. The most relevant ideas for our purposes are to be found in the later work of Sylvia Scribner (1984). Her goal was to understand 'flexible expertise', specifically within the context of the workplace, which she regarded as a powerful arena for developing domain-specific cognitive skills. She drew on Vygotsky's (1987) distinction between 'formal' and 'empirical' organizations of knowledge (Scribner and Sachs 1990, Scribner *et al.* 1991). Her approach to knowledge acquisition aimed to take into account its developmental character; the fact that knowledge is generally acquired 'for a purpose', in the context of doing a job and working with specific tools and symbols; and the impact of the type of domain. Specifically, she thought that 'formal' and 'empirical' domains may afford different kinds of mastery.

Recent work by her associates (Scribner *et al.* 1992, Di Bello 1996) has focused on workers in factories or repair shops who are learning a Computer Integrated Manufacturing technology called MRP-II. Particular attention is being given to the relationships between a worker's prior knowledge of manufacturing and that worker's specific knowledge of MRP-II concepts.

An analysis of day-to-day activity by workers with three different classes of job titles and levels of responsibility revealed two different patterns of individual job organization, 'constructive' and 'procedural' activities. Constructive activities have clearly defined goals and poorly defined means: the employee is free to develop a procedure or tool that accomplishes the goal in an iterative fashion, getting reactions from more knowledgeable superiors only after attempting a solution on his or her own. By contrast, procedural activities have a clearly specified means, even a set order of execution, but the goal of the procedure may not be clearly conveyed.

Constructive activities are associated with in-depth learning and flexible mastery, whereas procedural activities are associated with competence but not expertise—merely competent performers cannot deal with non-routine problems. Ongoing work on the effects of constructive and procedural activities has begun to produce evidence of multiple stages of development in MRP-II skill. A common 'growth error' is sorting items symmetrically instead of according to their proper vertical relationships in the MRP item hierarchy. This error is clearly constructed by the learners (it is not taught to them, nor does it derive from their prior knowledge of manufacturing). It seems to mark progress beyond the crudest misunderstandings of the item hierarchy, and a transition to a correct understanding of the vertical relationships in that hierarchy (Di Bello 1996). As with Piagetian approaches, the Vygotsky – Scribner treatment of expertise cannot be successfully applied unless researchers immerse themselves in the domain-specific details of the skills under development, the setting in which they are acquired, and the sequence in which they are typically mastered.

6. Beyond the binary paradigm

To recapitulate, we have noted that contemporary studies of expertise still most often restrict themselves to the static, binary comparisons typical of the novice – expert paradigm. Their methods are constricted under the pressure of a commitment to favour end-state knowledge description over accounts of the trajectories and processes of development. Breaking out of the binary paradigm will be possible only if we realize that expertise is inherently dynamic, flexible and emergent.

Our critique is not the only one that could be brought to bear on empirical studies of human expertise. In recent years, classical information-processing conceptions have been faulted from many quarters for being restricted to 'formal' domains, 'well-defined' problems, and laboratory environments. They have also been faulted for being concerned exclusively with expertise within the individual and ignoring the social context in which many forms of expertise actually function. For instance, the solitary hacker may predominate in popular thinking about computer programming, yet most programmers, whatever their preferred hours, work in teams, and programming expertise can't be fully understood without taking cooperation and task management into account (Curtis *et al.* 1988; for discussions of the social aspects of expertise in other fields, see Mathews *et al.* 1996, Di Bello 1996, and Shalin and Bertram 1996).

These days empirical research on expertise (for just a few examples, see Di Bello 1996, Klein *et al.* 1989, Shalin *et al.* in press, Shalin and Bertram 1996) is busily moving out of the laboratory into the field. We have no doubt that this is a salutary trend; our only point here is that ecological matters can get proper attention while developmental matters are still ignored. While some critics of IP conceptions (e.g. Dreyfus and Dreyfus 1986) have evident developmental concerns, others (e.g. Winograd and Flores 1986) exhibit virtually none. Consequently, ecologically motivated studies, while aiming for a richer description of expertise in its usual environment, may continue to overlook the process by which that expertise developed, or the means by which it is now being maintained and extended.

The longitudinal studies of skill acquisition that have begun to appear during the last decade (Staszewski, 1988) move in the right direction, but descriptions of intermediate steps along the trajectory, and considerations about developmental processes and constraints are also necessary. Working memory management and the Power Law of Practice will not be enough; qualitative change in knowledge, skills, goals, and even aesthetic criteria has to be acknowledged and described, and frameworks adequate to explain such qualitative change must be sought. Nor will invocations of metacognition suffice, so long as there are no theoretical resources to account for it. We have outlined two research strategies, one roughly Piagetian, the other roughly Vygotskian, which if more widely employed should help to remedy these deficiencies.

7. Toward genuine theoretical discussion

Although we regard Piagetian and Vygotskian research programmes in expertise as distinctly promising, we know that surprises and perhaps disappointments are in store. Coming up with an adequate theory of human development is a tough and contentious business, and in any case it wasn't our goal in this article (for one attempt at such a framework, see Bickhard and Campbell 1996).

We will naturally be pleased if more researchers undertake to use Feldman's approach to expertise, or Scribner's. But many will no doubt object to one or another feature of such approaches. Indeed, we would be enormously surprised if researchers in IP (or for that matter, in ecological but non-developmental traditions) didn't find plenty to criticize in our article. We will measure any success that this article might have, not by the number of converts it wins, but by the number of objections to it that get stated in public (and, consequently, serve to guide further discussion).

Presently, empirical research on expertise resembles most regions of psychology. It is the province of several different factions, each with its private territory of substantive and methodological assumptions. Open discussion of these assumptions is rare; usually they are held as 'hard core' commitments (Lakatos 1978) and brandished to confer justification on the study to be funded, or the article to be published (Bartley 1984, Campbell and Christopher, in preparation, Winegar and Valsiner 1992). We believe that future progress in the study of expertise depends on ample quantities of what is sometimes called 'cross-paradigm communication'.

Although it was much in evidence at the FLAIRS sessions from which these papers derive, such communication is not readily found today. How much frank discussion has there been between advocates of Piagetianism and advocates of IP? In the United States, representatives of each school have virtually ignored the theories of the other. In most IP publications, Piaget is occasionally cited as the author of tasks (such as number conservation) on which performance is to be explained, but not as the author of a psychological theory. There are entire edited volumes on expertise (such as Chi *et al*. 1988) in which Piaget (and Feldman and Vygotsky) are never mentioned at all. Meanwhile orthodox Piagetians have shrunk from any sort of engagement, constructive or otherwise, with IP accounts of learning. Little of value has passed between the factions, in Anglo-American psychology at any rate (Brown 1988).

There has been a similar absence of dialog between Piagetians and 'theory-change' advocates. A reader would never realize from the theory-change literature that a crucial part of Piaget's genetic epistemology attempted to draw informative parallels between the history of science and cognitive development within the individual. Nor is the theory-change literature informed by any recognition of the multiple difficulties that Piaget (1950), and Piaget and Garcia (1989) encountered when they explored these parallels. Some theory-change writings (e.g. Smith *et al.* 1985) even make use of Kuhn (1962) and Lakatos's (1978) ideas about the role of anomalies in theory-change—while ignoring the central role of similar anomalies in Piaget's (1985) theory of development.

Examples are easily multiplied, but the exercise would be depressing as well as space-consuming. And we have spoken only of the poor state of communication on the social science side. There are other walls between the study of human expertise and the design of expert systems, and these need breaking down as well.

8. Conclusion

We have analysed the research strategies and the preferred explanations that are characteristic of information-processing studies of expertise. The binary distinction between novices and experts is inadequate; studies based on it can't yield a rich description of the path towards acquiring expertise. Appeals to the chunking of production rules, to the compilation of declarative knowledge, or to the Power Law of Practice are inadequate to explain the way expertise is acquired. Developmental conceptions, we have argued, are better prepared to describe the path toward expertise and the processes by which it is acquired and maintained. 'Theory-change' conceptions and the global five-stage model offered by Dreyfus and Dreyfus fall short for the reasons we have given; extensions of the Piagetian framework and the Vygotskian framework strike us as more promising.

Up to now there has been remarkably little public discussion between advocates of Piagetian or Vygotskian constructivism, on the one hand, and advocates of IP or conventional AI on the other. Perhaps this special issue will spark some. Neither our article (nor any of the others in this special issue) offers the last word on any question about expertise. We do hope that what is said here, and elsewhere in this special issue, may serve as the first word—in a dialogue that has a long way to run.

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Notes

1. The very wording of this statement denies any distinction between expert performance and performance that is merely competent—another sign of the binary paradigm at work.
2. The single reference to qualitative changes in knowledge is a concession to the 'theory-change' school, which likens the development of expertise to theory change during the history of science. This school of thought is very much distinct from information processing, and is best understood as a failed developmental conception (see Section 5.1).
3. We leave to one side occasional lapses within the main information-processing tradition, such as Anderson's (1995) model of 'three stages of skill acquisition'. These so-called stages (cognitive, associative, and autonomous) are vague markers of progress toward holding one's knowledge in procedural form; all knowledge is thought to consist of 'declarative' propositions or encoded production rules, each largely independent of all of the others, and the only 'developmental' processes allowed within the theory are proceduralization (conversion of propositions into production rules) and

quantitative improvement in performance as described by the Power Law of Practice. Such stages are weak from a descriptive standpoint (indeed, palpably inferior in this regard to the global stages of Dreyfus and Dreyfus 1986, which we discuss in Section 5.2). More importantly, they come embedded in a theory of learning which ascribes very little importance to the order in which changes in knowledge occur; indeed, one that denies the very possibility of qualitative change in knowledge (Bickhard and Terveen 1995).

4. Work by Moshman and Franks (1986) on inferential validity, and by Kuhn *et al.* (1988) on conceptions of theory and data, provides *prima facie* evidence that children's understanding of logic does change over time. Samarapungavan's (1992) defence of the theory-change approach against Kuhn *et al.* makes light of differences that other conceptions would surely treat as developmental, such as the fact that elementary school children find it much easier to give an explanation for rejecting a claim that is inconsistent with empirical evidence than for rejecting a claim that is logically inconsistent. Besides, scientists' understanding of the 'scientific method' has undergone vast historical changes (Laudan 1984, Shapere 1984); the very idea that science involves generating hypotheses about unobservable processes and testing their consequences against data was not widely credited among Western scientists until the middle of the 19th century (Laudan 1981). The 'theory-change' conception makes no use of *this* historical parallel.
5. According to a story that circulates among former students of Piaget's, the school system in Geneva began teaching number conservation as part of its Kindergarten curriculum. Piaget was disgusted when he learned of this decision, and no more studies of number conservation were carried out in Geneva (although of course they continued elsewhere).

References

Adelson B. (1984) When novices surpass experts: The difficulty of a task may increase with expertise. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **10**: 483–495.

Anderson, J. R. (1995) *Cognitive Psychology and its Implications*, 4th edn (New York: W. H. Freeman).

Anderson, J. R., Conrad, F. G. and Corbett, A. T. (1989) Skill acquisition and the LISP tutor. *Cognitive Science*, **13**: 467–505.

Ashcraft, M. H. (1992) Cognitive arithmetic: A review of data and theory. *Cognition*, **44**: 75–106.

Bartley, W. W. III (1984) *The Retreat to Commitment*, 2nd edn (LaSalle, IL: Open Court).

Beach, K. D. (1990). *Rural Nepali students' reconstruction of mathematics while moving from school to work.* Paper presented at the annual meeting of the American Educational Research Association, Boston, MA.

Benner, P. (1984) *From Novice to Expert: Excellence and Power in Clinical Nursing Practice.* (Reading, MA: Addison Wesley).

Bereiter, C. and Scardamalia, M. (1993) *Surpassing Ourselves: An Inquiry into the Nature and Implications of Expertise* (Chicago: Open Court).

Bickhard, M. H. (1991) The import of Fodor's anti-constructivist argument. In L. Steffe (ed.), *Epistemological Foundations of Mathematical Experience* (New York: Springer) pp. 14–25.

Bickhard, M. H. and Campbell, R. L. (1989) Interactivism and genetic epistemology. *Archives de Psychologie*, **57**: 99–121.

Bickhard, M. H. and Campbell, R. L. (1996). Developmental aspects of expertise: Rationality and generalization. *Journal of Experimental and Theoretical Artificial Intelligence*, **8**, 399–417.

Bickhard, M. H. and Terveen, L. (1995) *Foundational Questions in Artificial Intelligence and Cognitive Science—Impasse and Solution.* (Amsterdam: North-Holland).

Brooks, R. E. (1977) Towards a theory of the cognitive processes in computer programming. *International Journal of Man-Machine Studies*, **9**: 737–751.

Brown, T. (1988) Ships in the night: Piaget and American cognitive science. *Human Development*, **31**: 60–64.

Campbell, R. L. (1990) Developmental scenario analysis of Smalltalk programming. In J. C. Chew and J. Whiteside (eds) *Human Factors in Computing Systems: CHI'90 Conference Proceedings* (New York: Association for Computing Machinery) pp. 269–276.

Campbell, R. L. and Bickhard, M. H. (1986) *Knowing Levels and Developmental Stages.* (Basel: S. Karger).

Campbell, R. L. and Bickhard, M. H. (1987) A deconstruction of Fodor's anticonstructivism. *Human Development*, **30**: 48–59.

Campbell, R. L. and Bickhard, M. H. (1992) Types of constraints on development: An interactivist approach. *Developmental Review*, **12**: 311–338.

Campbell, R. L., Brown, N. R. and Di Bello, L. A. (1992). The programmer's burden: Developing expertise in programming. In R. R. Hoffman (ed.) *The Psychology of Expertise: Cognitive Research and Empirical AI* (New York: Springer) pp. 269–294. (Reissued in 1994 by Erlbaum.)

Campbell, R. L. and Christopher, J. C. (in preparation). The empirical hyperspecialty system in psychology.

Carey, S. (1985) Are children fundamentally different kinds of thinkers and learners than adults? In S. Chipman, J. Segal and R. Glaser (eds), *Thinking and Learning Skills*, Vol. 2. (Hillsdale, NJ: Erlbaum).

Carraher, T. N., Carraher, D. W. and Schliemann, A. D. (1985) Mathematics in the streets and in the schools. *British Journal of Developmental Psychology*, **3**: 21–29.
Carroll, J. M. and Rosson, M. B. (1991) Deliberated evolution: Stalking the View Matcher in design space. *Human–Computer Interaction*, **6**: 281–318.
Carroll, J. M., Singer, J. A., Bellamy, R. K. E. and Alpert, S. R. (1990) A view matcher for learning Smalltalk. In J. C. Chew and J. Whiteside (eds) *Human Factors in Computing Systems: CHI'90 Conference Proceedings* (New York: Association for Computing Machinery) pp. 431–437.
Charness, N. (1989) Expertise in chess and bridge. In D. Klahr and K. Kotovsky (eds) *Complex Information Processing: The impact of Herbert A. Simon* (Hillsdale, NJ: Erlbaum) pp. 183–208
Chase, W. G. and Simon, H. A. (1973) The mind's eye in chess. In W. G. Chase (ed.) *Visual Information Processing* (New York: Academic Press).
Chi, M. T. H., Bassok, M., Lewis, M. W., Reimann, P. and Glaser, R. (1989) Self-explanations: How students study and use examples in learning to solve problems. *Cognitive Science*, **13**: 145–182.
Chi, M. T. H., Feltovich, P. J. and Glaser, R. (1981) Categorization and representation of physics problems by experts and novices. *Cognitive Science*, **5**: 121–152.
Cooke, N. J. (1990) Practice makes perfect—or does it? [Review of *The Nature of Expertise*, by Chi, Glaser, and Farr.] *Contemporary Psychology*, **35**: 251–253.
Curtis, B., Krasner, H. and Iscoe, N. (1988) A field study of the software design process for large systems. *Communications of the ACM*, **31**: 1268–1287.
D'Andrade, R. (1990) Some propositions about the relations between culture and human cognition. In J. W. Stigler, R. A. Shweder and G. Herdt (eds) *Cultural Psychology* (New York: Cambridge University Press).
Di Bello, L. (1996) Providing multiple "ways in" to expertise for learners with different backgrounds: When it works and what it suggests about adult cognitive development. *Journal of Experimental and Theoretical Artificial Intelligence*, **8**: 229–257.
diSessa, A. (1983) Phenomenology and the evolution of intuition. In D. Gentner and A. L. Stevens (eds) *Mental Models* (Hillsdale, NJ: Erlbaum) pp. 15–33.
Dreyfus, H. L. and Dreyfus, S. E. (1986) *Mind over Machine: The Power of Human Intuition and Expertise in the Era of the Computer* (New York: The Free Press).
Ericsson, K. A., Krampe, R. T. and Tesch-Römer, C. (1993) The role of deliberate practice in the acquisition of expert performance. *Psychological Review*, **100**, 363–406.
Ericsson, K. A. and Staszewski, J. J. (1989) Skilled memory and expertise: Mechanisms of exceptional performance. In D. Klahr and K. Kotovsky (eds) *Complex Information Processing: The Impact of Herbert A. Simon* (Hillsdale, NJ: Erlbaum) pp. 235–267.
Feldman, D. H. (1980) *Beyond Universals in Cognitive Development* (Norwood, NJ: Ablex).
Feldman, D. H. (1986) How development works. In I. Levin (ed.) *Stage and Structure: Reopening the Debate* (Norwood, NJ: Ablex) pp. 284–306.
Feldman, D. H. (1994a) Studies in the development of expertise. In D. H. Feldman (ed.) *Beyond Universals in Cognitive Development*, 2nd edn (Norwood, NJ: Ablex) pp. 121–143.
Feldman, D. H. (1994b) Cultural organisms. In D. H. Feldman (ed.) *Beyond Universals in Cognitive Development*, 2nd edn (Norwood, NJ: Ablex) pp. 161–185.
Fodor, J. (1972) Some reflections on L. S. Vygotsky's *Thought and Language*. *Cognition*, **1**: 83–95.
Fodor, J. (1981) The present status of the innateness controversy. In J. Fodor (ed.) *RePresentations.* (Cambridge, MA: MIT Press) pp. 257–316
Glaser, R. (1989) Expertise and learning: How do we think about instructional processes now that we have discovered knowledge structures? In D. Klahr and K. Kotovsky (eds) *Complex Information Processing: The Impact of Herbert A. Simon* (Hillsdale, NJ: Erlbaum) pp. 269–282
Gould, J. D. (1975) Some psychological evidence on how people debug computer programs. *International Journal of Man–Machine Studies*, **7**: 151–182.
Karmiloff-Smith, A. (1986) From meta-processes to conscious access: Evidence from metalinguistic and repair data. *Cognition*, **23**: 95–147.
Klein, G. A., Calderwood, R. and McGregor, D. (1989) Critical decision method for eliciting knowledge. *IEEE Transactions on Systems, Man, and Cybernetics*, **19**: 462–472.
Kuhn, D., Amsel, E. and O'Loughlin, M. (1988) *The Development of Scientific Thinking Skills.* (New York: Academic Press).
Kuhn, T. S. (1962) *The structure of scientific revolutions.* (Chicago: University of Chicago Press).
Lakatos, I. (1978) Falsification and the methodology of scientific research programmes. In J. Worrall and G. Currie (eds) *The Methodology of Scientific Research Programmes: Philosophical Papers Volume 1* (Cambridge: Cambridge University Press) pp. 8–101. (Originally published 1970.)
Larkin, J. H. (1981) Enriching formal knowledge: A model of learning to solve textbook physics problems. In J. R. Anderson (ed.) *Cognitive Skills and their Acquisition.* (Hillsdale, NJ: Erlbaum).
Laudan, L. (1981) *Science and Hypothesis: Historical Essays on Scientific Methodology* (Dordrecht: D. Reidel).
Laudan, L. (1984) *Science and Values: The Aims of Science and their Role in Scientific Debate* (Berkeley: University of California Press).

Lesgold, A., Rubinson, H., Feltovich, P. J., Glaser, R., Klopfer, D. and Wang, Y. (1988) Expertise in a complex skill: Diagnosing X-ray pictures. In M. T. H. Chi, R. Glaser and M. J. Farr (eds) *The Nature of Expertise* (Hillsdale, NJ: Erlbaum) pp. 311–343
Mathews, R. C., Lane, I. M., Roussel, L. G., Nagy, M. S., Haptonstahl, D. E. and Brock, D. B. (1996) Using conscious reflection, group processes, and AI to facilitate development of expertise. *Journal of Experimental and Theoretical Artificial Intelligence*, **8**: 259–276.
McCloskey, M. (1983) Naive theories of motion. In D. Gentner and A. L. Stevens (eds.) *Mental Models* (Hillsdale, NJ: Erlbaum) pp. 299–324
McKeithen, K. B., Reitman, J. S., Reuter, H. H. and Hirtle, S. C. (1981) Knowledge organization and skill differences in computer programmers. *Cognitive Psychology*, **13**: 307–325.
Moshman, D. and Franks, B. A. (1986) Development of the concept of inferential validity. *Child Development*, **57**: 153–165.
Neches, R., Langley, P. and Klahr, D. (1987) Learning, development, and production systems. In D. Klahr, P. Langley and R. Neches (eds) *Production System Models of Learning and Development* (Cambridge, MA: MIT Press) pp. 1–53.
Newell, A. (1990) *Unified Theories of Cognition*. (Cambridge, MA: Harvard University Press).
Newell, A. and Simon, H. (1972) *Human Problem Solving*. (Englewood Cliffs, NJ: Prentice-Hall).
Piaget, J. (1950) *Introduction à l'épistémologie génétique, Vol. 2: La pensée physique*. (Paris: Presses Universitaires de France).
Piaget, J. (1977) *Recherches sur l'abstraction réfléchissante* (2 Vols.) (Paris: Presses Universitaires de France).
Piaget, J. (1985) *The Equilibration of Cognitive Structures: The Central Problem of Intellectual Development*, Trans. T. Brown and K. J. Thampy. (Chicago: University of Chicago Press) (Originally published 1975.)
Piaget, J. and Garcia, R. (1989) *Psychogenesis and the History of Science*, trans. H. Feider. (New York: Columbia University Press).
Rogoff, B. (1990) *Apprenticeship in Thinking: Cognitive Development in Social Context* (New York: Oxford University Press).
Samarapungavan, A. (1992) Children's judgments in theory-choice tasks: Scientific rationality in childhood. *Cognition*, **45**: 1–32.
Scribner, S. (1984) Studying working intelligence. In B. Rogoff and J. Lave (eds.) *Everyday Cognition: Its Development in Social Context* (Cambridge, MA: Harvard University Press).
Scribner, S., Di Bello, L., Kindred, J. and Zazanis, E. (1992) *Coordinating knowledge systems: A case study*. Unpublished manuscript, Laboratory for Cognitive Studies of Activity, Graduate Center, City University of New York.
Scribner, S., and Sachs, P. (1990) *A study of on-the-job training*. Technical Paper No. 13. Washington, DC: National Center on Education and Employment.
Scribner, S. and Sachs, P., with Di Bello, L. and Kindred, J. (1991) *Knowledge acquisition at work*. Technical Paper No. 22. Washington, DC: National Center on Education and Employment.
Shalin, V. L. and Bertram, D. A. (1996). Functions of expertise in a medical intensive care unit. *Journal of Experimental and Theoretical Artificial Intelligence* **8**: 209–227.
Shalin, V. L., Geddes, N. D., Bertram, D., Szczepkowski, M. A. and DuBois, D. (in press) Expertise in dynamic, physical task domains. In P. J. Feltovich, K. Ford and R. R. Hoffman (eds) *Expertise in Context: Human and Machine*. (Cambridge MA: AAAI/MIT Press).
Shapere, D. (1984) *Reason and the Search for Knowledge: Investigations in the Philosophy of Science*. (Dordrecht: D. Reidel).
Sheil, B. A. (1981) The psychological study of programming. *ACM Computing Surveys*, **13**: 101–120.
Shneiderman, B. (1980) *Software Psychology* (Cambridge, MA: Winthrop).
Shweder, R. (1990) Cultural psychology—What is it? In J. W. Stigler, R. Shweder and G. Herdt (eds) *Cultural Psychology* (New York: Cambridge University Press).
Smith, C., Carey, S and Wiser, M. (1985) On differentiation: A case study of the concepts of size, weight, and density. *Cognition*, **21**: 177–237.
Soloway, E. and Ehrlich, K. (1984) Empirical studies of programming knowledge. *IEEE Transactions on Software Engineering*, **SE-10**: 595–609.
Spelke, E., Hirst, W. and Neisser, U. (1976) Skills of divided attention. *Cognition*, **4**: 215–230.
Spiro, R. J., Coulson, R. L., Feltovich, P. J. and Anderson, D. K. (1988) Cognitive flexibility theory: Advanced knowledge acquisition in ill-structured domains. *Tenth Annual Conference of the Cognitive Science Society* (Hillsdale, NJ: Erlbaum) pp. 375–383.
Staszewski, J. J. (1988) Skilled memory and expert mental calculation. In M. T. H. Chi, R. Glaser and M. J. Farr (eds) *The Nature of Expertise* (Hillsdale, NJ: Erlbaum) pp. 71–128.
Vosniadou, S. and Brewer, W. F. (1987) Theories of knowledge restructuring in development. *Review of Educational Research*, **57**: 51–67.
Vygotsky, L. S. (1987) Thinking and speech (N. Minick, Trans.). In R. Rieber and A. S. Carton (eds) *The Collected Works of L. S. Vygotsky, Vol. 1: Problems of General Psychology* (New York: Plenum) pp. 39–288. (Originally published 1934.)

Walton, R. E., Adams, M. L., Goldsmith, L. T. and Feldman, D. H. (1988) *Affect and development in a nonuniversal domain*. Paper presented at the Jean Piaget Society meeting, Philadelphia.

Wertsch, J. V. (ed.) (1985) *Culture, Communication, and Cognition*. (London: Cambridge University Press).

Wiedenbeck, S. and Scholtz, J. (1996) Adaptation of programming plans in transfer between programming languages: A developmental approach. In W. D. Gray and D. A. Boehm-Davis (eds) *Empirical Studies of Programmers: Sixth Workshop* (Norwood, NJ: Ablex) pp. 233–253

Winegar, L. T. and Valsiner, J. (1992) Contextualizing context: Analysis of metadata and some further elaborations. In L. T. Winegar and J. Valsiner (eds.) *Children's Development within Social Context, Vol. 2: Research and Methodology* (Hillsdale, NJ: Erlbaum) pp. 249–266

Winograd, T. and Flores, F. (1986) *Understanding Computers and Cognition: A New Foundation for Design*. (Norwood, NJ: Ablex).

Wiser, M. and Carey, S. (1983) When heat and temperature were one. In D. Gentner and A. L. Stevens (ed.) *Mental Models* (Hillsdale, NJ: Erlbaum) pp. 267–298