

Artefacts and cognitive development: how do psychogenetic theories of intelligence help in understanding the influence of technical environments on the development of thought?

Pierre Vérillon, Colette Andreucci, INRP

Technology education and pupils' cognitive development

Scholarly English language publications concerning technology education have considerably increased during the past years. However, as several recent reviews of literature have pointed out (De Miranda, 2004; Zuga, 2004), focus has essentially been on the design, development and assessment of curriculum. The prevailing approaches have left aside issues relating to the cognitive processes underlying student and teacher activity in the classroom. As a result, our knowledge of the singular nature and forms of cognition involved in the construction and transmission of technical knowledge and skills remains very scant. Some writers (Cajas 2000, Lewis 1999; Petrina, 1998, Zuga, 2004) link this deficiency to insufficient theoretical grounding and faulty problematics in research on technology education.

In France, the situation is quite similar. Studies in technology education have focused as elsewhere essentially on curriculum design and assessment. As A. Weill-Barais (1995), a psychologist of physics education, has stated: *“One can only observe the scarcity of research on how children access to technical objects... The specificity of technical objects generally goes unrecognised by developmental psychologists although it would warrant a psychogenetic approach. This lack of recognition leads to a situation where no manual or reader in psychology is available on the subject.”*

Technology education is a recent subject in the French national curriculum. Only since 1985 is it, for all pupils, a compulsory subject taught by specialized (trained technology) teachers during the four years of middle school. Prior to that date, precursory forms of technology education as a separate subject had existed on and off at different levels in the school system for the previous century. However these were optional and only concerned certain categories of pupils and were often taught by physics teachers. Thus, in France, until the permanent introduction of technology in the curriculum, only the pupils enrolled in technical and vocational branches of the education – often on account of their poor results in the academic subjects - were actually confronted during their schooling with technological environments, activities and issues relating to industry, crafts and commerce. It is noteworthy that, today still, part of technology teacher training is carried out by technical and vocational education teachers and that most teacher trainees are former students of technical and vocational schools.

As regards the French research and development community in technology education, it is far from equalling in numbers and seniority those that have evolved around other school subjects. Even so, its existence actually predates the subject's entry into the curriculum. Curriculum design and testing was carried out as early as the 70's and eventually led to the founding of the LIREST (now LIREST), a university research lab that has now become prominent in technology curriculum studies. Likewise, at the National Institute for Pedagogical Research (INRP), a department dedicated to studies in technical and vocational education developed

psychological and pedagogical approaches to teaching technological knowledge and skills. In particular, the learner's interaction with material and semiotic artefacts of the technical environment became a major topic of interest and research within the department in the 80's. Twenty years later, in continuity with these seminal interrogations and despite this department's dissolution, a theoretical and thematic line of work has been maintained and developed among a community now scattered inside and outside the institute. The aim of this paper is to give an account by two insiders of the conceptual change this community has both experienced and brought about in the approach of learning and development within technological settings. It describes how, drawing from theoretical and empirical evidence, research has led to a critical appraisal these two models and derived alternative propositions resting on their stronger points, such as Vygotsky's notion of mediated activity, and his conception of signs and tools as instruments as well as Piaget's vision of cognitive development as resulting from the child's active alteration of his (her) environment. Three examples will illustrate these alternative models: the first deals with some unsuspected effects of child-artefact interaction on the construction of the concept of volume, the second deals with tool use and the development of activity, the last with learning to read engineering drawings.

Some history

One of the unforeseen results of the advent of technology education in 1985 has been the emergence in French psychological research of a new field of study – instrumented activity in human–artefact interaction – and the development of a new theoretical paradigm, the instrumental theory (Rabardel, 1995; Vérillon & Rabardel, 1995) now developing in work psychology and ergonomics.

The story begins at the Département d'Etudes et de Recherche sur les Enseignements technologiques of INRP where two long-term INRP research programs headed by Pierre Rabardel and involving both INRP and university researchers were launched in 1984. The first program, entitled "*Made material objects as support for cognitive development in education*", arose from the realization that technology education would introduce into the arena of learning activities objects sharply contrasting with the discursive and textual objects usually associated with other school subjects. Its aim was to investigate if - and how - interaction with made material objects¹, by reason of their material, finalized and functional nature, would affect cognition. The focus of the research agenda was clearly developmental: can pupils' dealings with artefacts within school organized settings, whether as objects of study or as means of action, influence their cognitive development and, if so, what are the determining conditions? The empirical work attempted to give evidence of cognitive change or growth resulting from situations in which pupils, in order to solve a problem or fulfil a task, had to design and/or build and/or use a material object.

The second research program, entitled "*Reading difficulties in engineering drawing*", aimed at understanding the difficulties encountered by pupils in decoding engineering drawings, then considered a key skill in technical and vocational education. The dawning technology education was also expected to benefit from this program, as one of the objectives of new curriculum was to familiarize middle school pupils with engineering drawing. The work carried out within this program centred on analysing readers' errors and designing remedial material and tasks.

¹ Fairly rapidly, through the group's interest in anthropological issues the phrase "made material object" (*objet matériel fabriqué*) was abandoned in favour of "artefact". See Rabardel (1995) for discussion.

The predominance of Piagetian genetic constructivism

A remarkable point is that the conceptual frameworks summoned by the researchers involved in both these programs all derive from Piagetian constructivism, clearly dominant at the time in French educational psychology. In the early 80's, the works of Vygotsky and Bruner were just being translated and still practically unknown to researchers. Consequently, Piagetian constructivism seemed the most appropriate framework for investigating developmental processes.

Here are some significant empirical studies carried out under the first program:

- How do situations in which pupils build and use different types of weighing-machines influence their conception of weight/ length of beam ratio?
- How do spatial competencies evolve in woodworking activities involving tool use?
- How does everyday experience with familiar objects designed to vary in shape and size influence the child's construction of volume?
- How does pupils' experience of work with a lathe influence their conception of surface?

The hypotheses underlying these studies were clearly inspired by Piagetian theory. The assumption was that, in compliance with Piaget's model of cognitive equilibration (1975), the subjects' existing cognitive structures, when brought to bear on the specific structural and functional properties of made objects, would in the course of assimilation/accommodation bring about conceptual change. This was actually evidenced by some experiments: for example, pupils having been involved in woodworking fared better in spatial tests than did those of a control group.

In the second program, again Piaget provided the theoretical framework for research. In conceptualising the cognitive processes underlying competency in reading engineering drawings, approaches based on Piaget's theory of the construction of the representation of space bore fruitful results. For example, many errors committed by students in reading tasks could be explained by their incapacity to grasp projective operations or to apply them when decoding the different orthographic views of an object. In a typical experiment, pupils were faced with oblique drawings of blocks of different shapes, of which they were also given top and front orthographic views. Their task was to draw a side view of each block. On analysis, many errors seemed to result from an impulse of students to conserve, and consequently reproduce, in their drawing of a side view some significant or outstanding feature of the front view. In keeping with Piagetian theory, which shows figurative thought to genetically precede operative thinking, these errors were attributed to students' use of figurative strategies whereas responses that showed evidence of mental coordination of the top and front views were considered as resulting from operative strategies (Vermersch P. & Weill-Fassina A., 1985).

Thus, genetic constructivism seemed to be, on the whole, a very satisfactory framework for the interpreting the evidence yielded by empirical work. However, some results did not entirely fit with theory thus revealing possible "anomalies" in the paradigm. If some instances of child-artefact interaction seemed to conform to the equilibration theory, other experiments were less conclusive. For example, exposure of children to telescopic, folding or inflatable objects in everyday contexts seemed to unbalance their construction of the invariance of volume. Likewise, progress in the geometrical modelling of the spatial aspects of turning, brought about by running a lathe, was shown to be due not to the subjects' interaction with the

machine but to their gradual awareness of physical and spatial invariants in the course of their joint interaction both with the lathe and the work piece during the machining process. Similarly, concerning engineering drawing, Rabardel (1982) had already shown that some errors in reading tasks could also be induced by faulty comprehension of the object described by the drawing. Other errors (Vérillon & Rabardel, 1987) could be attributed to student's misconceptions as to how engineering drawing actually works (i.e., how the semiotic and geometrical solutions embodied in engineering drawing enable the production of accurate graphic descriptions of technical artefacts).

In the next section, we have a closer look at some of these studies.

Three studies in pupil-artefact interaction

Conceptualising volume

The first study (Andreucci, 1990) concerns an analysis of the difficulties met by children in acquiring the conservation (the invariance) of volume. Since Piaget, Inhelder and Szeminska's (1948) seminal studies of children's spontaneous geometry and their acquisition of physical quantities (1941), it is well known that the development of volume, as a physical and geometrical construct, comes very slowly and lately. Before 11 or 12 years, a child will not admit that a same piece of clay, rolled in a ball will occupy an equal amount of space as when rolled in a cylinder. Nor will he (she) predict that, immersed in a glass, it will raise the water to the same level. By contrast, the same child, using logical arguments which would apply also for this situation - identity, reversibility, compensation - will be quite sure of the invariance of the quantity of matter of that piece of clay (acquired around 8 years) and of its weight (around 10) when it undergoes the same transformations. Rather unsatisfyingly, Piaget explains this puzzling lag in the generalization of a logical structure to different notions as a horizontal "décalage" due to the specific resistance of the notion to assimilation within the structure. Other studies focusing on volume as a measure or quantifier of space have evidenced similar enduring difficulties in pupils' acquisition of the concept. Ricco, Vergnaud & Rouchier (1983) show that, at age 15, most pupils have trouble with the aspects linked to the trilinear aspect of volumic quantification. However, all these studies, focusing exclusively on a physics or mathematical approach of the conceptualisation of volume, have overlooked a possible source of difficulty - i.e., that the child's representations of volume linked to practical everyday interaction with three-dimensional artefacts might lead to conflict with scholarly notions.

A look at technical documents and catalogues shows that the measurements of artefacts are generally given in terms of overall dimensions rather than in terms of volume. The notions associated with the bulk (in French, *encombrement*) or amount of space occupied by an object are evidently close to that of volume, but their physical and mathematical characteristics remain nonetheless different.

Bulk is expressed in three dimensions but in contrast with volume, these dimensions cannot be combined, nor are they interchangeable, in the sense that an artefact generally has a definite orientation in space, linked to its functional properties. In stowing or packing an artefact, for example, each dimension is taken into account separately. The fact that in everyday life, bulk rather than volume is most often the practical concept for dealing with the spatial problems posed by artefacts can explain the difficulty of conceiving volumetric space as a product of three dimensions.

Moreover, bulk, as a sociological and technological characteristic of material artefacts, does not manifest the same invariance as volume. First, unlike plasticine or clay objects used by Piaget, most artefacts do not, for obvious functional reasons, easily undergo changes in shape without damage. When they do, it is generally because they have been designed in that intention (e.g.: telescopic, folding or inflatable objects). For instance, their utility being intermittent, they are designed so that, when not in use, they can be easily stowed or transported (e.g.: an umbrella, an ironing table or an air mattress). Also, bulkiness is a relative notion: it depends on relationships among other objects. Children will consider that objects imbedded in one another "take up less space room". Similarly they may consider that the space occupied by an object can vary, since it may or may not fit into a container according to the way it is introduced.

In studying the stowing techniques that children, aged between 5 and 12, use when asked to pack into a suitcase as many items as possible within a collection of everyday objects, we have shown that very early (around 7) they become aware that, as a result of design, the space occupied by artefacts is indeed a variable and relative characteristic. In ways not foreseen by Piaget, bulk or apparent volume, as a functional concept for thinking about objects in space (especially made objects), not only precedes the construction of volumetric concepts but, unknown to teachers and pupils, it may in fact become an impediment to this construction.

Interacting with devices for producing ruled surfaces

Another experiment (Verillon & Rabardel, 1995) consisted of asking a group of pupils, aged 10 to 15, to individually imagine ways of producing plane and revolution (cylindrical and conical) surfaces on pieces of wood. We were interested in seeing how the children, through the different technical processes they would suggest, would tackle both the underlying mechanical and spatial aspects of the material transformation.

The task was to transform a rectangular block of wood into a cylinder (or, inversely, a cylinder into a parallelepiped, or again a parallelepiped into a cone, etc.). In order to minimize language bias, the question actually asked was: "How would you make an object with this shape here from an object like that one there?" The objects (representing both the initial workpiece and the end-product), which the subjects they could handle at will, were in solid wood, approximately 100 x 30 x 30 mm.

In short, the transformation technique proposed by all the pupils consists in removing matter from the work piece. This is carried out in two phases: rough-cutting then finishing through abrasion. Each phase is associated with a particular class of instruments: knives, cutters and saws (even a power-saw!) for rough-cutting and files, abrasives, etc. for finishing.

As regards the management of the spatial aspects of the operation, the desired end shape seems, so to speak, projected by the subject on to the rough work piece. This projection, which is mental - though some children actually suggest drawing lines on the block - guides the step by step removal of matter from the work piece, until, through successive approximations, it "matches" the anticipated shape as near as possible.

The lack of particular constraints in the procedure to be used enabled the subjects to build and solve the problem in terms of tools, as well as technical and spatial schemes, which were familiar to them. Nevertheless, none of the pupils thought that the process that they suggested

was the same as that used in industry to produce similar shapes. As expressed by one of them: "That's done with machines, otherwise it would take too much time ... and then, anyway, a machine is more accurate!"

We therefore followed up by asking them how they imagined such machines.

The relative diversity of the mechanized solutions suggested by the children contrasts with the procedure anticipated for manual manufacture, which is practically identical from one subject to another. Leaving aside one subject's initial proposal consisting of a sort of remote manipulating device capable of reproducing the manual procedure through a system of rods with terminal clamps, they may be grouped into three categories according to the technical solution anticipated to produce the desired transformation:

- moulding or deformation,
- removal of matter through abrasion,
- removal of matter by cutting.

The constraint of mechanizing their manufacturing process considerably transforms the task for the subjects. The main element at stake and the principal difficulty introduced by this constraint concerns the management of the spatial and temporal aspects of transformation. In the non-mechanized procedures, control of the amplitude and direction of the transforming action is provided by the hand holding the tool. Similarly, as regards the planning of action, the deviation from the anticipated final state is managed in a retroactive way, step by step, under the control of successive sightings, possibly facilitated by the reference marks drawn on the work piece. What characterizes the manual procedures is a lack of a general spatial coordination of action (which, for example, could take into account properties of axial symmetry or revolution). In our opinion, it is precisely because these procedures do not require any overall geometrization or synchronization of the transformation process that they are so readily proposed.

Conversely, the instruction to mechanize the process is interpreted as entailing attributing to the machine the management of the energetic, chronological and spatial aspects of the transformation – hence, the need to equip the device with the physical and geometrical operators capable of producing the desired shape in a direct and proactive way. The remote manipulator solution, which conserves retroactive adjustment and the ability to operate the removal of matter on a step-by-step basis, appears to be an attempt to get round this hard necessity. Finding an adequate design solution effectively requires addressing multiple and complementary problems concerning the physical aspects of the transformation, the spatial analysis of the desired final form, as well as, correlatively, the geometry of the generating organ, the locus of its successive positions, etc.

The devices imagined by the pupils - other than remote manipulators - demonstrate that this is reached through a geometric analysis (or breaking down) of the desired form and, at the same time, a corresponding dissociation of the means of its production. This joint dissociation of both the desired shape and its generating mechanism is carried out to a variable extent in the devices imagined by the children. Thus, moulding devices enable the shape to be conserved fully (i.e. without having to be broken down) within the geometry of the die, simply by reversing it. As one pupil asserts: "if you want to get that shape, the machine has to have the same shape". On the other hand, transformation by machining does not enable the desired shape to be conserved in the tool. Thus, devices driving abrasive strips in translation for the production of plane surfaces, while still partially conserving the anticipated form, are

evidence of an analysis in terms of surface. Pushing geometric abstraction a step further, other systems using cutting edges and points, actuated by controlled movements, within different spatial arrangements, reveal their designer's capacity, at least "in action", to dissociate the initial shape into generator points or lines in liaison with revolution axes and directors.

The observation of these pupils' first acquaintance with a miniature lathe revealed similar processes. For most of the pupils, the idea of being able to produce a cylindrical surface using a single rectilinear longitudinal stroke only appears at a late stage. As a matter of fact, the sole idea of being able to remove matter from a piece of metal was in itself difficult to conceive for them: "metal is too hard!" Only after having tried different step by step strategies for "wearing away" or "cutting" metal along the work piece was it possible for them to become aware of certain invariant spatial properties of the lathe, imparted to it by its very design: for example, the fact that the distance between the tool and the rotational axis of the work piece remains invariant across action on the lathe's longitudinal handwheel.

This implies that the subject is able to decentre himself from his own actions so that he can resituate and coordinate them in an overall space. In effect, only the conscious discovery, or the discovery "in action" of the spatial characteristics underlying his procedures - often linked to their failure - enables the subject to recompose them and, for instance, to become aware of the relations of equivalence between a cutting edge of a given shape and a generator point with a suitable trajectory, or again between the iteration of elementary operations and their composed form.

Reading engineering drawing

The study of the child's development of what Piaget and Inhelder's (1947) termed "representative space" enabled decisive breakthroughs in the understanding of the errors made in reading engineering drawings. Expertise in reading drawings was seen as the ability to carry out the mental transformations – in Piagetian terms: "projective operations" – that enable the reader to mentally "visualize" what, in a view of an object, varies and what remains invariant as he modifies his point of view on that object. Different projective operations involved in reading were identified (Zougarri G. et al, 1984) and shown to be of unequal difficulty for learners. A diagnostic test and material for remedial training in these different operations were designed (Higelé, 1984).

However despite the undeniable value, both predictive and pragmatic, of these findings, there were some weaknesses in the approach. For example, in the reading experiments and in the remedial tasks, the objects depicted in the drawings – geometric blocks of differing shapes - were far from resembling the usual referents of engineering drawings, i.e. industrial artefacts. Similarly, the graphic mode used for their representation was quite distant from the actual graphic code and norms used in engineering drawing.

Studies carried out with real drawings and in functional contexts confirmed the importance of readers' mastery of spatial operative invariants. However they also revealed that certain spatial properties of the industrial artefacts depicted in engineering drawings are also invariants. The geometric characteristics of made objects are not – contrary to blocks – technologically neutral: the shape of an artefact is determined both by its functional properties (e.g. the thread of a screw, the wing of an airplane) and by constraints imposed by the means available to fabricate it (e.g. machine tools are limited in the shapes they can generate). The reader's knowledge of these regularities – his technological culture – was shown to influence

his decoding of drawings (Rabardel, 1982; Bal et al, 1984). So alongside the need for spatial skills, reading drawings was seen as also requiring a technological acquaintance with the objects depicted. However, yet another dimension plays a part in student's reading difficulties: it is the extent to which they master the fairly complex code implemented in engineering drawing.

This code comprises several sub-systems or components (Rabardel, 1980). A descriptive component provides the underlying projective principles (i.e. orthogonal projection, oblique projection, etc.) that enable the production of views that conserve certain dimensional or geometric aspects of the depicted object. When coupled with a second component – the graphic system that furnishes the different line symbols used in drawing - material representations of the depicted object can be made. Finally, a third component, the conventional disposition of the different views in the 2-dimensional space of the drawing enables the reader to identify and mentally interconnect the different points of view on the depicted object in 3-dimensional space. Suggestions for the explicit teaching of the semiotics of engineering drawing as well as of other graphic codes encountered in vocational and technology education were made (Vérillon & Rabardel, 1987; Andreucci et al, 1996)

Another look at genetic epistemology

What the three above studies show is that, contrary to what would be expected within a classic Piagetian framework, the construction by a subject of the properties of made objects – whether they be material or symbolic - stems not solely from his (her) bilateral interaction with that object. In order to understand cognitive development resulting from human dealings with artefacts it is necessary take into account the subject's conceptual construction, jointly: of the artefact, of the reality on which it is brought to bear and of the resulting interaction between artefact and reality. In this section, we attempt to show why Piaget's constructivism may not be totally adequate in explaining human development in the made world and why it is necessary to appeal to other psychological theories.

The epistemic subject

It is first of all important to keep in mind that Piaget's constant aim was to reveal the mechanisms underlying "the child's construction of reality" (1937). His explicit project is to account for the development of what he termed the "epistemic subject" In this sense, his focus was on the genetic processes and mechanisms through which the human subject elaborates knowledge about the surrounding social and physical world. In our opinion, the aim of a genetic psychology of technique should, in contrast, be to focus on the "pragmatic subject". There is a need to describe and account for the mechanisms through which humans devise pragmatic projects and means aimed at conforming the world to their designs. In this perspective, action retains the decisive role it plays in constructivism (Inhelder, B., & Cellier, G., 1992). However, it is no longer an action upon the environment aiming as with Piaget at eliciting its invariant properties. It is rather an action mobilizing knowledge concerning these stable and predictable patterns of the environment in order to put it to use advantageously. Technical action, through the design and use of artefacts, imparts artificial properties on the natural environment. In its search for beneficial and pragmatic effects, it strives to introduce novel invariant relationships among elements of existing reality. Which doesn't mean that no knowledge may be produced within the sphere of technique. On the contrary, Staudenmaier (1985) argues that whenever technological development may be stemmed by lack of knowledge in a given field, "problematic data" is then generated to meet

the specific demands of the design problem. Likewise, Perrin (1991) shows that artefact design is a major source of knowledge. However, he adds that the production of knowledge in technology differs from the scientific process of knowledge production in that it is only secondary and accessory to artefact production that remains “both the starting and end point of the design process”. In this sense, we consider that what is needed is psychological insight into the design process equivalent to the insight brought by genetic epistemology into the knowing process.

Biologism

There is, in our opinion, another intrinsic limitation to applying the Piagetian model to interaction with the made world – a limitation that it shares with other approaches of cognition: it is its naturalistic point of view. It sees development as an epigenetic process: much as a biological organism develops through adaptation to its milieu, the epistemic subject is conceived as constructing his (her) cognitive structures by interacting with the environment. Initially, reality may resist assimilation and destabilize these structures but ultimately, through accommodation, they restructure thereby gaining stability and strength. A follower of Descartes and Kant regarding the philosophy of knowledge, Piaget seems to consider both his subject’s environment and his (her) means of interaction with this environment as immune from social and historical influence. Language and artefacts, for example, have no particular status in his theory that might set them fundamentally apart from the world of physical or living objects. When investigating the construction of children’s conceptions in mechanics, he may ask his subjects to comment the trajectory of a toy car on an inclined plane or that of a toy boat in a basin. However it is clear that these toys are used only because they are particularly convenient in demonstrating certain invariants of the physical world. Not surprisingly, might comment a technologist: the car wheels, the ship’s rudder are artificial invariants, historically and socially brought about and transmitted. They shrewdly and profitably exploit the “laws of nature”. In short they are artefacts, but this peculiarity is not taken into account by theory.

Dualism

One last problem raised by the Piagetian approach is its fundamentally dualistic conception of subject-environment interaction, which leads research to focus on dyadic relationships: subject-object, man-machine, student-teacher, student-curriculum, etc. The subject is always studied in his (her) face-to-face relationship with the world or a sub-set of the world. The idea of a mediated relationship is absent from this approach. This is consistent with the other aspects we have highlighted in this section: on the one hand, an exclusively constructivist and epistemic conception of development, and on the other, a biologist and a-historical view of human interaction with reality. Yet, as pointed out by French philosopher of technique, J. -P. Séris (1994), technique is inherently “interposition of mediations, be they instrumental (tools, machines, institutions) or methodical (manoeuvres, procedures, programs, processes)” (P. 48). In keeping with this analysis, a psychological theory striving to account for human cognitive functioning and development in technological settings should reserve a prominent status to mediation and mediational processes. In the following section,

we sketch out some theoretical elements worked out during the last two decades that attempt to contribute to such a theory.

Towards a theory of instruments

Vygotsky is stated as having said " the central point of our psychology is mediation " (Wertsch, 1985). However mediation does not appear to have been a major concept in the psychological paradigms that dominated the second half of the 20th century. As Norman (1991) once pointed out, "despite the enormous impact of artefacts upon human cognition, most of our scientific understanding is of the [...] single, unaided individual, studied almost entirely within the university laboratory ". Unknowingly, some of the early work at INRP on interaction with made objects or with industrial graphics was liable to this criticism. But, as we have seen, the contradictions raised by empirical work soon showed the need for added reflection on the exact nature of artefacts. Readings in early 20th century psychological literature brought back into focus the issue of instruments and instrumented activity much researched in Europe before World War II (Rabardel & V erillon, 1988). The instrumental nature of artefacts gradually imposed itself and it became obvious that interaction with artefacts could not be understood within a dyadic subject-object relationship. Of course, artefacts belong to the objective world but, as instruments, they necessarily intervene as "interfaces" between the subject and the world. In consequence, a triadic model of instrumented activity (Rabardel & V erillon, 1985; V erillon & Rabardel, 1995; V erillon, 2000) was proposed (Fig. 1).

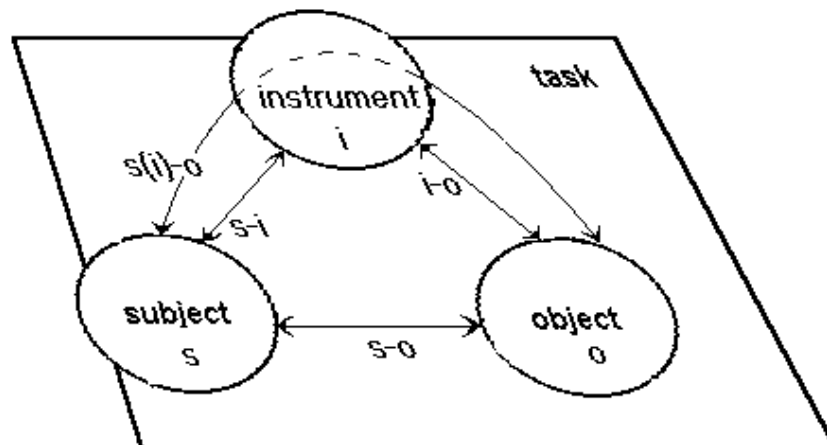


Fig. 1: The situated instrumented activity model

In contrast with the classic dyadic modelling of subject-object interaction, it underscores the multiple relationships that, in instrumented activity, bind together the subject, the instrument and the object towards which instrumented action is directed. It also indicates that instrumented activity is always grounded in – and hence conditioned by – situated tasks. Our study of pupils’ first encounter with a lathe showed that the analysis of instrumented activity could not be limited to considering only direct subject-instrument interaction (s-i). The model shows it should also take into account direct subject-object interaction (s-o), as well as instrument-object interaction (i-o) and indirect subject-object interaction through the mediation of the instrument (s(i)-o).

Semiotic artefacts, such as engineering drawing, can also be seen as instruments (Vérillon & Rabardel, 1993; Andreucci et al, 1996). Just as for any artefact, their structural properties can be analysed functionally. For example, the semiotic and geometric properties of engineering drawing are not arbitrary. On the contrary, they are motivated by the type of information – essentially regarding shape and dimension – required in engineering tasks. As already mentioned, functional teaching of these properties is possible.

Vygotsky (1985a) termed instruments such as drawings and other symbolic artefacts “psychic instruments”, in the sense that what they affect is not an object but one’s own - or another person’s – psyche, as shown in figure 2.

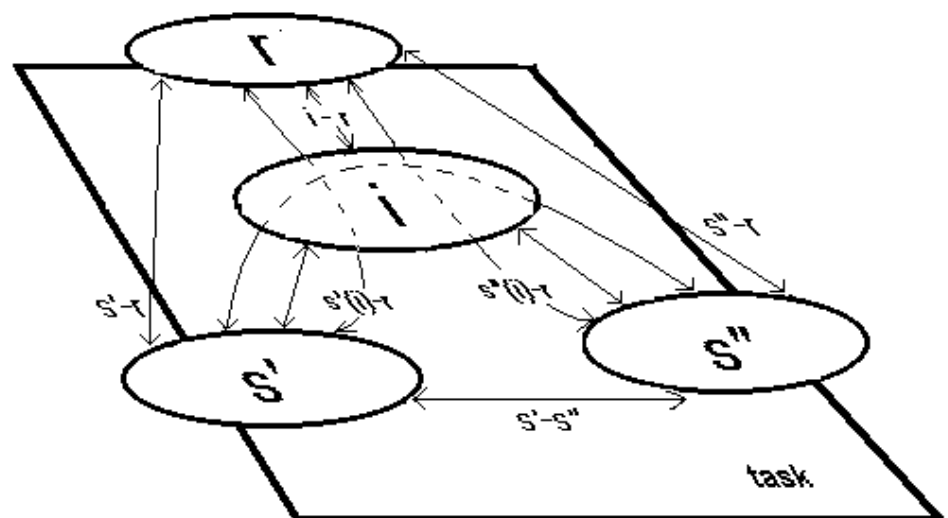


Fig. 2: Situated activity instrumented by a semiotic artefact

Modelling activity instrumented by semiotic artefacts is a bit more complex than modelling that instrumented by material instruments. The model represents communication as taking place between two subjects (s' and s'') by means of the semiotic instrument (i). Also, since semiotic instruments aim at modifying a receiver’s information state or representations, a fourth element has been introduced: that about which there is information or representation - the referent (r). The referent is the object (or object class) to which refers the transmitter’s instrumented action on the receiver. The model consequently shows the two-fold function of semiotic instruments: a signalling function resulting in the sensory and cognitive stimulation

of the receiver and a referring function, which enables the subjects to relate the signal to an external object. A new set of relationships can be examined through this model. Instrument-referent relations (i-r) concern coding, that is the set of semiotic solutions that enable the transmission of information concerning the referent through signifiers (e.g. the specific graphic symbols in engineering drawing). Subject-referent relationships (s'(i)-r and s''(i)-r) indicate a subject's relation to a referent object during coding and decoding. Direct s-r relationship points to knowledge, representations and actual, virtual or remembered perceptions that s' or s'' may have of the referent object.

Distinguishing artefacts and instruments

These models of instrumented activity can help understanding how and in what ways artefacts affect cognitive development. But first it is necessary to make a clear distinction between artefact and instrument. Artefacts are man-made material constructs. They are bodies of intentionally organized invariants designed to operate certain anticipated transformations of the human or material environment when put to use by a person. As such artefacts are only one component of instrumented action. The other component consists of the activity brought into play by the user of the artefact. Artefacts display both their function and their efficiency only through the operations of their user. Like words that have lost their meaning, tools of which the use has been lost can no longer become instruments even though they remain artefacts. In this sense, an artefact in order to qualify as an instrument requires the psychological and physical participation of a user. When in use, an artefact is caught up in a system of action schemes, representations, knowledge, intellectual and motor skills that alone actualises its function. In this sense, instruments are actually hybrid entities, part psychological and part artefactual (Rabardel, 1995).

Instrumental genesis

Artefacts become instruments for people through a process referred to by Rabardel as "instrumental genesis". As the above studies reveal, it can be a long and difficult process before a lathe or engineering drawing can become instruments. A look at the models shows why: many relationships have to develop in the course of instrumental genesis. Appropriation is a word that well describes this process. It indicates the two directions in which this process takes place: towards the self and towards outside reality.

In its first sense, appropriation indicates that the artefact has to be integrated within one's own cognitive structure – i.e. one's existing representations, available action schemes etc, which in general require adaptation. Often, socially formed utilization schemes exist which have to be learned from peers. This self-directed construction, which mainly concerns s-i relationships in our models, is termed "instrumentation". The second sense of the word indicates that the artefact has to be appropriated to outside context. Specific ends and functional properties - some not necessarily intended by design - are attributed to it by the user. This is termed "instrumentalization" and concerns mainly s(i)-o and i-o relationships and s'(i)-r, i-r, s'(i)-s" and i-s" relationships, for semiotic artefacts.

Instrumentation and instrumentalization both contribute mastering artefacts. As his (her) utilization schemes evolve, the user can observe the consequences on the artefact's behaviour and on artefact-object interaction. In return, his representations of the functional aspects of his mediated action (e.g. causal relationships involved in tool-object interaction) can cause him (her) to alter his (her) schemes. Our observations of pupils learning through discovery to man

a lathe illustrate this interdependence between instrumentation and instrumentalization. Machining operations evolved gradually as certain technical characteristics were uncovered and taken into account by the pupils.

People's instruments develop at different rhythms and over different lengths of time. Consider the career of a professional pilot: the scope of his instrument – its “instrumental field” – both deepens and widens as he accumulates experience and incorporates continuous technological change. Instrumented technical activities can be seen to evolve along two lines of development, distinct although more or less linked: a line of operative development and a line of artefactual development. Operative development is tied to the extension of the transformations made possible by the integration of artefacts in a person's repertoire of means of action. As the artefact is put to use, novel effects appear, which in order to be repeated and controlled require the formation of new schemes. At the same time new properties (new invariants) are manifested causing the subject to modify or renew his (her) existing representations concerning the artefact, the reality on which it operates or the processes and transformations at hand. New objectives for artefact use can consequently be contemplated by the user, thus opening up possibility of renewed activity and mobiles. Operative development may take different forms:

- increased speed, power and discrimination of utilization schemes,
- scheme transfer from one artefact, or class of artefacts, to another,
- developing different schemes for an identical result,
- developing new schemes for original or extreme results...

Artefactual development is linked to the fact that artefact use is guided by the expectation of interesting effects that by design, if correctly manipulated, the artefact is supposed to produce. Thus in the course artefact use, the user is led to assign finalities and functional properties to the artefact. However, in each situated instance of use, because contextual conditions vary, the artefact is never engaged the same way, nor in ways always in conformity with its design. In a sense, each singular or novel use of an artefact redesigns it. This does not result in actual modification of the artefact, but the user's vision of the artefact, of its functional properties and of the effects it is liable to produce, changes. Think of someone using a spanner as a hammer. According to Rabardel (1995), through people's changing uses of artefacts, the design process continues well after their actual fabrication.

Operative and artefactual development cannot be conceived separately from what actually gives them significance: the subject's activity. For Vygotsky (1978), tool and symbol are brought into effect through the mediation of human activity. However this doesn't mean they submit passively to activity. Artefacts and activity influence each other in ways that leads the development of activity and of instrumental genesis to be closely associated, recalling Vygotsky's (1985b) concept of zone of proximal development. At first, an artefact (a lathe, for instance), not yet become an instrument, is for the subject but a mere promise of potential action, out of reach of his present possibilities. Yet, within reach are social models to be imitated and, on the artefact, perceptible characteristics - wheels, handles – that afford indication of possible operation. These generate a certain tension: new potential activity is envisioned, along with novel outcomes, and they trigger the appropriation process. With the beginning of instrumental genesis, activity starts to be realised. And as remarked Léontiev (1975): “realised activity is always more fertile and more genuine than the consciousness that anticipates it”. Unexpected properties and possibilities become apparent and, consequently, visions change, new goals are set, schemes accommodate and new motives arise. Instrumented activity, enriched by its confrontation with reality, in return stimulates

instrumental development. A circular movement of mutual development and renewal is initiated: developing activity demanding new operative and artefactual progress while these open up novel fields of action.

Conclusion

Empirical and theoretical work in psychology over the last 20 years at France's National Institute of Pedagogical Research has attempted to document the idea that cognition is not brought to bear on artefacts in the same way as it is on natural objects. Of course, like any constituent of the environment, artefacts confront cognition with a set of constraints it has to identify, understand and take into account. As such they partake in the resistance that the objective world opposes to human understanding and, in this sense, Piaget's "epistemic subject" can be seen as a model of how human understanding copes with this - indistinctly made or natural - world. Very much in the way of a scientist, he experiments and probes his environment in search of invariance and logical coherence. Quite understandably, it has proved very fruitful for the comprehension of learning in science education settings.

Yet artefacts also exert specific constraints related to their mediational and instrumental nature. These constraints pertain to their built-in functional and structural features as devices designed to produce transformations, and no longer just to their general physical characteristics, which are common to all material objects. One set of constraints is linked to the mental and material operations required of artefact users in order to effectively carry out, in a given context, a given transformation. These constraints account for some of the misconceptions concerning volume discussed in our first study: practical experience of certain artefacts focused users' attention on a number of their functional spatial characteristics in detriment of others, not functional in the context, yet useful for the conceptualisation of volume.

Another set of constraints pertains to the particular set of material transformations a given artefact is designed to enable. This type of constraints is the one with which the pupils of our second experiment were essentially coping as they pondered on ways of configuring and implementing mechanisms capable of generating different surfaces. In dealing with semiotic artefacts such as engineering drawing, as in our third study, pupils coped with similar, albeit semiotic, constraints. Their difficulties in reading were seen as resulting from the fact that they do not comprehend the functionality of these constraints.

Obviously, the "epistemic" framework is not pertinent here, in the sense that we are dealing with behaviour that is at once practical and mediated. In search of an alternative model, our present work seeks theoretical guidelines in both post-Piagetian Genevan authors and the vigotskian tradition. In the former, we find insight into what might be termed a theory of "pragmatic" cognition, in which action is not, as in Piaget's conception, orientated towards the production of knowledge, but in which, on the contrary, knowledge is activated and processed by the subject so as to elicit practical and utilitarian transformations of his environment. In the latter, we find the basis for a psychological model of instrumentation, that is a model of the cognitive process whereby artefacts, at first undifferentiated from other objects, progressively acquire instrumental value, are integrated into one's mental and physical interaction with the world and finally, in return modifies it. Addressing these two dimensions, the pragmatic and the instrumental, seems quite crucial if we are to better understand the early forms of cognition and development in technological contexts, as they appear in technology education.

References

- Andreucci, C. (1990). *Influence de la structure des matériels dans la genèse des activités de classification*. Rapport de recherche, INRP, 38 p.
- Andreucci, C., Froment, J.P., & Verillon, P. (1996). Contribution à l'analyse des situations d'enseignement / apprentissage d'instruments sémiotiques de communication technique, *Aster*, 23, 185-215.
- Bal, J.J., Rabardel P., & Vérillon, P. (1984). Présenter la géométrie du dessin technique. In *L'apprentissage de la géométrie du dessin technique: des constats d'échec et des moyens de réussite* (pp. 13-47). Collection Rapports de Recherche n°9. Paris: INRP.
- Cajas, F. (2000). Research in Technology Education : What Are We Researching , A response to Theodore Lewis, *Journal of Technology Education*, 11(2), 61-69.
- De Miranda, M. A. (2004). The grounding of a discipline: cognition, and instruction in technology education, *International Journal of Technology and Design Education*, 14, 61-77.
- Higelé, P. (1985). L'apprentissage des opérations projectives. In *L'apprentissage de la géométrie du dessin technique* (pp. 117-162). Collection Rapports de Recherche n°9. Paris: INRP.
- Inhelder, B., & Cellier, G., Eds. (1992). *Le cheminement des découvertes de l'enfant*. Neuchâtel: Delachaux et Niestlé.
- Leontiev, A. (1975). *Activité, conscience, personnalité*. Moscou : Editions du Progrès.
- Lewis, T. (1999). Research in Technology Education. Some areas of need. *Journal of Technology Education*, 10, 2, 41- 59.
- Norman, D. A. (1991). Cognitive artefacts. In CARROLL J. (Ed.), *Designing interaction*, (pp. 17-38). N.Y.: Cambridge university Press.
- Perrin, J. (1991). Sciences de la nature et sciences de l'artificiel: deux processus différents de production de connaissances. In Perrin, J. (Ed.), *Construire une science des techniques* (pp. 381-397). Limonest: L'interdisciplinaire.
- Petrina, S. (1998). The Politics of Research in Technology Education : A critical Content and Discourse Analysis of The Journal of Technology Education, *Journal of Technology Education*, 10, (1), 27-57
- Piaget, J. (1975). *L'équilibration des structures cognitives*. Paris: PUF.
- Piaget, J., & Inhelder, B. (1941). *Le développement des quantités chez l'enfant*. Neuchâtel: Delachaux & Niestlé.
- Piaget, J. (1937). *La construction du réel chez l'enfant*. Neuchatel : Delachaux et Niestlé.

- Piaget, J., & Inhelder, B. (1947). *La représentation de l'espace chez l'enfant*. Paris: P.U.F.
- Piaget, J., Inhelder, B., & Szeminska, A. (1948). *La géométrie spontanée de l'enfant*. Paris: PUF.
- Rabardel, P. (1980). *Contribution à l'étude de la lecture du dessin technique*. Thèse de 3^o cycle, Paris: E.H.E.S.S..
- Rabardel, P. (1982). Influence des représentations préexistantes sur la lecture du dessin technique. *Le Travail Humain*, 2.
- Rabardel, P. (1995). *Les hommes et les technologies*. Paris: Armand Colin.
- Rabardel, P., & Vérillon, P. (1985). Relations aux objets et développement cognitif. In A. Giordan & J.L. Martinand (Eds). *Acte des septièmes journées internationales sur l'éducation scientifique*. Paris: LIREPT, Université Paris VII, 189-196.
- Rabardel, P., & Vérillon, P. (1988). Le statut de l'objet matériel fabriqué chez Piaget, Léontiev, Wallon et Vygotski. Unpublished paper, INRP.
- Ricco, G., Vergnaud, G. & Rouchier, A. (1983). Représentation du volume et arithmétisation, entretiens individuels avec des élèves de 11 à 15 ans. *Recherches en didactiques des mathématiques*, 4/1, 27-69.
- Séris, J. P. (1994). *La technique*. Paris: PUF.
- Staudenmaier, J. (1985). *Technology's storytellers*. Cambridge: MIT Press.
- Vérillon, P., & Rabardel P. (1987). L'intériorisation du système projectif du dessin technique. In Rabardel, P., & Weill-Fassina, A. (Eds.), *Le Dessin Technique* (pp. 109-118). Paris: Hermès.
- Vérillon, P., & Rabardel, P. (1993). De l'analyse des compétences à l'élaboration des contenus: contribution de la psychologie et de la sémiologie à la conception en ingénierie didactique. In Bessot, A., & Vérillon, P. (Eds.), *Espaces graphiques et graphismes d'espaces*. Grenoble: La Pensée Sauvage.
- Vérillon, P., & Rabardel, P. (1995). Cognition and artefacts : a contribution to the study of thought in relation to instrumented activity. *European Journal of Psychology of Education*, X, (1), 77-101.
- Vérillon, P. (2000). Instruments and cognition : Piaget and Vygotsky revisited in search of learning model for technology education. *The Journal of technology Studies*, 26 (1), 3-10.
- Vermersch, P. & Weill-Fassina, A. (1985). Les registres de fonctionnement cognitif: application à l'étude des conduites de lecture et d'écriture du dessin technique élémentaire. *Le Travail Humain*, 48 (4), 331-340.
- Vygotsky, L. S. (1930/1985a). La méthode instrumentale en psychologie.

Vygotsky, L. S. (1931/1978). *Mind and society*. Harvard University Press, Cambridge, Massachusetts.

Vygotsky, L. S. (1934/1985b). *Pensée et langage*. Paris : Editions sociales.

Weill-Barais, A. (1995). Genèse des rapports de l'enfant à l'objet technique. *Actes du 68^e Congrès de l'AGIEM*, Metz.

Wertsch, J. V. (1985). La médiation sémiotique de la vie mentale; L.S. Vygotsky et M. M. Bakhtine. In Schneuwly, B., & Bronckart, J.P. (Eds.), *Vygotsky aujourd'hui* (pp. 39-47). Neuchâtel: Delachaux et Niestlé.

Zougari, G., Weill-Fassina, A., & Vermersch, P. (1984). Performances et compétences d'élèves de LEP dans des épreuves de lecture de forme. In *L'apprentissage de la géométrie du dessin technique* (pp. 207-286). Collection Rapports de Recherche n°9. Paris: INRP.

Zuga, K.F. (2004). Improving technology education research on cognition. *International Journal of Technology and Design Education*, 14, 79-87.