The evolution of research on collaborative learning

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Abstract. For many years, theories of collaborative learning tended to focus on how individuals function in a group. More recently, the focus has shifted so that the group itself has become the unit of analysis. In terms of empirical research, the initial goal was to establish whether and under what circumstances collaborative learning was more effective than learning alone. Researchers controlled several independent variables (size of the group, composition of the group, nature of the task, communication media, and so on). However, these variables interacted with one another in a way that made it almost impossible to establish causal links between the conditions and the effects of collaboration. Hence, empirical studies have more recently started to focus less on establishing parameters for effective collaboration and more on trying to understand the role which such variables play in mediating interaction. In this chapter, we argue that this shift to a more process-oriented account requires new tools for analysing and modelling interactions.

1. Introduction

For many years, theories of collaborative learning tended to focus on how individuals function in a group. This reflected a position which was dominant both in cognitive psychology and in artificial intelligence in the 1970s and early 1980s, where cognition was seen as a product of individual information processors, and where the context of social interaction was seen more as a background for individual activity than as a focus of research in itself. More recently, the group itself has become the unit of analysis and the focus has shifted to more emergent, socially constructed, properties of the interaction.

In terms of empirical research, the initial goal was to establish whether and under what circumstances collaborative learning was more effective than learning alone. Researchers controlled several independent variables (size of the group, composition of the group, nature of the task, communication media, and so on). However, these variables interacted with one another in a way that made it almost impossible to establish causal links between the conditions and the effects of collaboration. Hence, empirical studies have more recently started to focus less on establishing parameters for effective collaboration and more on trying to understand the role which such variables play in mediating interaction. This shift to a more process-oriented account requires new tools for analysing and modelling interactions.

This chapter presents some of the major developments over recent years in this field, in both theoretical and empirical terms, and then considers the implications of such changes for tools and methods with which to observe and analyse interactions between learners. In so doing, we have tried to address both the work done in psychology and in distributed artificial intelligence (DAI). However, we have to acknowledge that this chapter has a bias towards psychology — not only because it reflects the interests of the authors to a large extent, but also because DAI has focused more on cooperative problem solving than on collaborative learning.

At this point we need to make a brief comment on this distinction: learning versus problem solving and collaboration versus cooperation. While psychologists consider that learning and problem solving are similar processes, computer scientists still address them separately. Different research communities (DAI versus machine learning, for example) have developed different techniques, some for learning and some for problem solving. The 'collaboration' versus 'cooperation' debate is more complex. Some people use these terms interchangeably. (Indeed, there is some disagreement amongst the authors themselves.) For the purposes of this chapter, in acknowledgement of distinctions that others in the field have made, we stick to a restricted definition of the terms. “Collaboration" is distinguished from "cooperation" in that cooperative work "... is accomplished by the division of labor among participants, as an activity where each person is responsible for a portion of the problem solving...", whereas collaboration involves the "... mutual engagement of participants in a coordinated effort to solve the problem together." (Roschelle & Teasley, in press).

Defining collaboration by the non-distribution of labour does not avoid ambiguities. Miyake has shown that some spontaneous division of labour may occur in collaboration: "The person who has more to say about the current topic takes the task-doer's role, while the other becomes an observer, monitoring the situation. The observer can contribute by criticising and giving topic-divergent motions, which are not the primary roles of the task-doer." (Miyake, 1986; p. 174). O'Malley (1987) reported similar results with pairs attempting to understand the UNIX C-shell command interpreter. This distribution of roles depends on the nature of the task and may change frequently. For example, in computer-supported tasks, the participant who controls the mouse tends to be "executor", while the other is likely to be the "reflector" (Blaye, Light, Joiner, & Sheldon, 1991). Cooperation and collaboration do not differ in terms of whether or not the task is distributed, but by virtue of the way in which it is divided: in cooperation, the task is split (hierarchically) into independent subtasks; in collaboration, cognitive processes may be (heterarchically) divided into intertwined layers. In cooperation, coordination in only required when assembling partial results, while collaboration is "... a coordinated, synchronous activity that is the result of a continued attempt to construct and maintain a shared conception of a problem" (Roschelle & Teasley, in press).

2. Theoretical Issues: the individual or the group as the unit

What is the nature of the dyad in collaborative learning? It can be viewed as comprising two relatively independent cognitive systems which exchange messages. It can also be viewed as a single cognitive system with is own properties. These two different answers to the question serve to anchor the two ends of the theoretical axis. At one end, the unit of analysis is the individual. The goal for research is to understand how one cognitive system is transformed by messages received from another. At the other end of the axis, the unit of analysis is the group. The challenge is to understand how these cognitive systems merge to produce a shared understanding of the problem. Along this axis, between the ‘individual' and the 'group', we can find three different theoretical positions: socio-constructivist, socio-cultural and shared (or distributed) cognition approaches.

In this chapter we talk about an 'evolution' along this axis because the social end has recently received more attention — maybe because it has been previously neglected. We do not mean to imply than one viewpoint is better than another: scientists need both pictures from microscopes and pictures from satellites. Moreover, for the sake of exposition, the approaches will be presented as more different than they actually are. Both Piaget and Vygotsky acknowledge the intertwined social and individual aspects of development (Butterworth, 1982).

2.1. The socio-constructivist approach

Although Piaget's theory focused mainly on individual aspects in cognitive development, it inspired a group of psychologists (the so-called "Genevan School") who in the 1970s undertook a systematic empirical investigation of how social interaction affects individual cognitive development (cf. Doise & Mugny, 1984). These researchers borrowed from the Piagetian perspective its structural framework and the major concepts which were used to account for development: conflict and the coordination of points of view (centrations). This new approach described itself as a socio-constructivist approach: it enhanced the role of *inter*-actions with others rather than actions themselves.

The main thesis of this approach is that "...it is above all through interacting with others, coordinating his/her approaches to reality with those of others, that the individual masters new approaches" (Doise, 1990, p.46). Individual cognitive development is seen as the result of a spiral of causality: a given level of individual development allows participation in certain social interactions which produce new individual states which, in turn, make possible more sophisticated social interaction, and so on.

Despite this theoretical claim, which suggests a complex intertwining between the social and the individual plane, the experimental paradigm used by its proponents involved two supposedly "individual" phases (pre- and post-test), separated by an intervention session in which subjects worked either alone (control condition) or in pairs. Evidence showed that, under certain conditions, peer interaction produced superior performances on individual post-test than individual training (for reviews, see Doise & Mugny, 1984; Blaye, 1988). The studies which established this tradition of research involved children in the age-range 5-7 years, and relied essentially on Piagetian conservation tasks. Where working in pairs facilitated subsequent individual performance, the mediating process was characterised as "socio-cognitive conflict", i.e. conflict between different answers based on different centrations, embodied socially in the differing perspectives of the two subjects. The social dimension of the situation was seen as providing the impetus towards or catalyst for resolving the conflict. Such resolution could be achieved by transcending the different centrations to arrive at a more advanced "decentred" solution.

From this perspective, the question was asked: under which conditions might socio-cognitive conflict be induced? One answer was to pair children who were, from a Piagetian perspective, at different stages of cognitive development. However, it was emphasised that subsequent individual progress cannot be explained by one child simply modelling the other, more advanced, child. It has been repeatedly demonstrated that "two wrongs can make a right" (Glachan & Light, 1981). What is at stake here, then, is not imitation but a co-ordination of answers. Subjects at the same level of cognitive development but who enter the situation with different perspectives (due to spatial organisation, for instance) can also benefit from conflictual interactions (Mugny, Levy & Doise, 1978; Glachan & Light, 1982).

Researchers in DAI report similar empirical results. Durfee et al (1989) showed that the performance of a network of problem solving agents is better when there is some inconsistency among the knowledge of each agent. Gasser (1991) pointed out the role of multiple representations and the need for mechanisms for reasoning among multiple representations (see Saitta, this volume). These findings concern the heterogeneity of a multi-agent system. Bird (1993) discriminates various forms of heterogeneity: when agents have different knowledge, use various knowledge representation schemes or use different reasoning mechanisms (induction, deduction, analogy, etc.). For Bird, heterogeneity is one of the three dimensions that define the design space for multi-agent systems. The other dimensions, distribution and autonomy, will be discussed later.

The success of the concept of conflict in computer systems is not surprising. This logical concept can be modelled in terms of knowledge or beliefs and integrated in truth maintenance systems or dialogue models. However, the main proponents of socio-cultural theory now admit that their view has probably been too mechanistic (Perret-Clermont et al., 1991). Blaye's empirical studies (Blaye, 1988) have highlighted the limits of "socio-cognitive conflict" as "the" underlying causal mechanism of social facilitation of cognitive development. Disagreement in itself seems to be less important than the fact that it generates communication between peer members (Blaye, 1988; Gilly, 1989). Bearison et al. (1986) reported that non-verbal disagreement (manifested for instance by moving the object positioned by the partner) was not predictive of post-test gains.

The role of verbalisation may be to make explicit mutual regulation processes and thereby contribute to the internalisation of these regulation mechanisms by each partner (Blaye, 1988). This interpretation leads us to the socio-cultural theory discussed in the next section.

2.2. The socio-cultural approach

The second major theoretical influence comes from Vygotsky (1962, 1978) and researchers from the socio-cultural perspective (Wertsch, 1979, 1985, 1991; Rogoff, 1990). While the socio-cognitive approach focused on individual development in the context of social interaction, the socio-cultural approach focuses on the causal relationship between social interaction and individual cognitive change. The basic unit of analysis is social activity, from which individual mental functioning develops. Whereas a Piagetian approach sees social interaction as providing a catalyst for individual change, often dependent upon individual development, from a Vygotskian perspective, inter-psychological processes are themselves internalised by the individuals involved. Vygotsky argued that development appears on two planes: first on the inter-psychological, then on the intra-psychological. This is his “genetic law of cultural development”. Internalisation refers to the genetic link between the social and the inner planes. Social speech is used for interacting with others, inner speech is used to talk to ourselves, to reflect, to think. Inner speech serves the function of self-regulation.

A simple computational model of internalisation has been developed by Dillenbourg and Self (1992). The system includes two agents able to argue with each other. The agent's reasoning is implemented as an argumentation with itself (inner speech). Each learner stores the conversations conducted during collaborative problem solving and re-instantiates elements from the dialogue for its own reasoning. The learner may for instance discard an argument that has been previously refuted by its partner in a similar context. The psychological reality is of course more complex, what takes place at the inter-psychological level is not merely copied to the intra-psychological, but involves an active transformation by the individual.

The mechanism through which participation in joint problem solving may change the understanding of a problem is referred to as “appropriation” (Rogoff, 1991). Appropriation is the socially-oriented version of Piaget's biologically-originated concept of assimilation (Newman, Griffin and Cole, 1989). It is a mutual process: each partner gives meaning to the other's actions according to his or her own conceptual framework. Let us consider two persons, A and B, who solve a problem jointly. A performs the first action. B does the next one. B's action indicates to A how B interpreted A's first action. Fox (1987) reported that humans modify the meaning of their action retrospectively, according to the actions of others that follow it. From a computational viewpoint, this mechanism of appropriation requires a high level of opportunism from agent-B, which must integrate agent-A's contribution, even if this action was not part of his plans.

Like the previous approach, this theory also attaches significance to the degree of difference among co-learners. Vygotsky (1978) defined the “zone of proximal development” as “...the distance between the actual developmental level as determined by independent problem solving and the level of potential development as determined through problem solving under adult guidance or in collaboration with more capable peers.” We will see that this concept is important to understand some empirical results.

Research in DAI does not directly refer to Vygotskian positions. This is somewhat surprising since the issue of regulation, which is central to the socio-cultural theory, is also a major issue in DAI. In computational terms, regulation is more often referred to as a an issue of 'control' or 'autonomy'. For Bird (1993), it constitutes the second dimension of the design space for multi-agent systems. As in political structures, there exist centralised systems where control is achieved by a super-agent or a central data structure (e.g., blackboard architectures) and decentralised systems in which each agent has more autonomy. An agent is more autonomous if it executes local functions without interference with external operations (execution autonomy), if it chooses when and with whom it communicates (communication autonomy) and whether it self-organises into hierarchical, serial or parallel sub-processes (structural autonomy) (Bird, 1993).

2.3. The shared cognition approach

The concept of shared cognition is deeply intertwined with the 'situated cognition' theory (Suchman, 1987; Lave, 1988 — see also Mandl, this volume). For those researchers, the environment is an integral part of cognitive activity, and not merely a set of circumstances in which context-independent cognitive processes are performed. The environment includes a physical context and a social context. Under the influence of sociologists and anthropologists, the focus is placed largely on the social context, i.e. not only the temporary group of collaborators, but the social communities in which these collaborators participate.

This approach offers a new perspective on the socio-cognitive and the socio-cultural approaches, and has recently led to certain revisions by erstwhile proponents of the earlier theories. Perret-Clermont et al. (1991), for example, question the experimental settings they had previously used for developing the socio-constructivist approach. They noticed that their subjects tried to converge toward the experimenter's expectations. The subjects' answers were influenced by the meaning they had inferred from their social relationship with the experimenter. Wertsch (1991) makes similar criticisms against work in the socio-cultural tradition: social interactions are studied as if they occur outside a social structure. Through language, we acquire a culture which is specific to a community. For instance, we switch grammar and vocabulary rapidly between an academic seminar room and the changing rooms of a sports centre. But overall, beyond a vocabulary and a grammar, we acquire a structure of social meanings and relationships (Resnick, 1991) that are fundamental for future social interactions.

This approach challenges the methodology used in many experiments where the subjects perform post-tests individually, often in a laboratory setting. More fundamentally, this approach questions the theoretical bases on which the previous ones rely: "... research paradigms built on supposedly clear distinctions between what is social and what is cognitive will have an inherent weakness, because the causality of social and cognitive processes is, at the very least, circular and is perhaps even more complex" (Perret-Clermont, Perret and Bell, 1991, p. 50). Collaboration is viewed as the process of building and maintaining a shared conception of a problem (Roschelle & Teasley, in press). While the previous approaches were concerned with the inter-individual plane, the shared cognition approach focuses on the social plane, where emergent conceptions are analysed as a group product. For instance, it has been observed that providing explanations leads to improve knowledge (Webb 1991). From the 'individualist' perspective, this can be explained through the self-explanation effect (Chi, Bassok, Lewis, Reimann & Glaser, 1989). From a 'group' perspective, explanation is not something delivered by the explainer to the explainee. As we will see in section 5, it is instead constructed jointly by both partners trying to understand each other (Baker, 1991).

The idea that a group forms a single cognitive system may appear too metaphorical to a psychologist. It does not surprise a computer scientist. While the natural scale for a psychological agent is a human being, the scale of a computational agent is purely arbitrary. The (vague) concept of agent is used to represent sometimes a single neurone, a functional unit (e.g., the 'edge detector' agent), an individual or even the world. The granularity of a distributed system, i.e., the size of each agent, is a designer's choice. It is a variable that the designer can tune to grasp phenomena that are invisible at another scale. It supports systems with different layers of agents with various scales, wherein one may compare communication among agents at level N and communication among agents at level N+1. Dillenbourg and Self (1992) built a system in which the same procedures are used for dialogue among agents and for each agent's individual reasoning. Hutchins (1991) reports a two-layer system wherein he can tune communication patterns among the units of an agent (modelled as a network) and the communications among agents. According to the respective strengths of intra-network and inter-network links, he observes an increase or a decrease of the group confirmation bias which cannot be reduced to individuals' contributions. Gasser (1991) insists on properties of multi-agent systems which "will not be derivable or representable solely on the basis of properties of their component agents" (p. 112).

3. Empirical Issues: effects, conditions and interactions

Not surprisingly, the different theoretical orientations we have just outlined have tended to employ rather different research paradigms. Generally, socio-cognitive experiments concerned two subjects of approximately the same age (or the same developmental level) while the Vygotskian setting involved adult-child pairs. Moreover, the Piagetian and Vygotskian paradigms used different collaborative tasks. We come back to these differences later. Other paradigms have been used independently of a particular theoretical framework, for instance the 'reciprocal teaching' paradigm (Palincsar and Brown, 1984; Palincsar, 1987; Riggio et al., 1991) in which one learner plays the teacher's role for some of the time and then shift roles with the other learner. We can also distinguish empirical work according to the size of the groups involved (dyads versus larger groups) or ways in which mediating technologies are employed, as in computer-supported collaboration.

There are also differences between the various approaches in terms of the research methods employed. In the socio-cognitive perspective, the methodology was to set up conditions hypothesised to facilitate learning and to compare the outcomes of this intervention with some control group. With such methods, collaboration is treated as a black box; the focus is on outcomes. In contrast, research from a socio-cultural point of view tends to employ micro genetic analyses of the social interaction. The focus is on the processes involved in social interaction. This is partly because of the importance attached to the concept of mediation in socio-cultural theory. Evidence is sought from dialogue for symbols and concepts which mediate social activity and which can in turn be subsequently found to mediate individual activity. The shared cognition approach obviously also favours the second methodology.

Despite their intertwining, we have attempted to disentangle the different research paradigms and theoretical approaches. In what follows we describe the 'evolution' of empirical research within three paradigms that differ with respect to the number and the type of variables that are taken into account.

3.1 The "effect" paradigm

Experiments conducted to answer the question "is collaborative learning more efficient than learning alone?" were fairly straightforward. The independent variable was 'collaborative work' versus 'work alone'. The choice of the dependent measures varied according to what the investigators meant by 'more efficient'. The most frequent measure was the subject's performance when solving alone the task they previously solved with somebody else. Some researchers decomposed this dependent variable into several other measures of performance, such as the improvement of monitoring and regulation skills (Brown & Palincsar, 1989; Blaye & Chambres, 1991) or a decrease in the confirmation bias. Within this paradigm, the precise analysis of effects is the only way to understand the mechanisms that make collaborative learning efficient.

This kind of research let to a body of contradictory results, within which the positive outcomes largely dominate (Slavin, 1983; Webb, 1991). Nevertheless, negative results cannot always be discarded as the result of experimental errors or noise. Some negative effects are stable and well documented, for instance the fact that low achievers progressively become passive when collaborating with high achievers (Salomon and Globerson,1989; Mulryan, 1992). There is a simple way to understand the controversial effects observed with the first paradigm: collaboration is in itself neither efficient or inefficient. Collaboration works under some conditions, and it is the aim of research to determine the conditions under which collaborative learning is efficient. This brings us to the second paradigm.

3.2 The "conditions" paradigm

To determine the conditions under which collaborative learning is efficient, one has to vary these conditions systematically. While the first experimental approach (in very general terms) varies only in terms of the dependent measures, the second experimental approach varies along two dimensions, both dependent and independent variables. Numerous independent variables have been studied. They concern the composition of the group, the features of the task, the context of collaboration and the medium available for communication. The composition of the group covers several other independent variables such as the number of members, their gender and the differences between participants. It is not possible here to give a complete overview of the findings concerning each of these variables. We will illustrate the work with three examples.

3.2.1 Group heterogeneity

Group heterogeneity is probably the most studied variable. Scholars have considered differences with respect to general intellectual development, social status or domain expertise. They have considered objective and subjective differences in expertise (whether the subjects are actually different or just believe themselves to be so). We restrict ourselves here to objective differences between the task knowledge of each subject, a parameter which is relevant for DAI. For the socio-constructivist, this difference provides the conditions for generating socio-cognitive conflict. For the socio-cultural approach, it provides conditions for internalisation. However, the nature of differences differs within each theoretical approach. Socio-cognitive theory refers to symmetrical pairs (i.e., symmetrical with respect to general intellectual or developmental level) where members have different viewpoints, whilst socio-cultural theory is concerned with asymmetric pairs where members have different levels of skill. Piaget (1965) argued that interaction with adults leads to asymmetrical power relations or social status, and that in such interactions adults or more capable children are likely to dominate. The pressure to conform in the presence of someone with higher perceived status is not likely, in this view, to lead to genuine cognitive change. Nonetheless, Rogoff (1990) notes that many studies from a Piagetian perspective have involved pairing, for example, conservers with non-conservers. This is hardly pairing children of equal intellectual ability and is more consistent with the Vygotskian position. The point of difference between the two approaches then is not one of "equal" versus "unequal" pairs, but exactly what this equivalence entails. Researchers have attempted to determine the optimal degree of differences. If it is too small, it may fail to trigger interactions. If the difference is too large, there may be not interaction at all. For instance, in a classification task, Kuhn (1972) shown children solutions reflecting a difference of -1, 0 , +1 or +2 levels compared to their own solutions. He only observed significant improvement in the +1 condition. This notion of optimal difference also emerges in DAI where Gasser (1991) notes that agents need a common semantics even to decide that conflict exists! The 'zone of proximal development' defines an optimal difference in an indirect way, i.e. not as a difference between subjects A and B, but as a difference between how A performs alone and how A performs with B's assistance.

Heterogeneity is also function of the size of the group. Empirical studies showed that pairs are more effective than larger groups, but heterogeneity is not the only factor that intervenes. Groups of three are less effective because they tend to be competitive, whilst pairs tend to be more cooperative (Trowbridge, 1987). However, differences between group sizes seem to disappear when children are given the opportunity to interact with other in the class (Colbourn & Light, 1987).

3.2.2 Individual prerequisites

A second set of conditions defines some prerequisites to efficient collaboration. It seems that collaboration does not benefit an individual if he or she is below a certain developmental level. We consider here the absolute level of the individual, not his or her level relative to the other group members. According Piaget, for a conflictual interaction to give rise to progress, it must prompt individual cognitive restructuring. This implies that a resolution of conflict which would be exclusively based on social regulations (compliance from one partner for instance) would prevent interaction from being efficient. Piaget's theory predicts that pre-operational children lack the ability to decentre from their own perspective and therefore benefit from collaborative work. Indeed, as others have noted (Tudge & Rogoff, 1989), Piagetian theory in this respect leads to something of a paradox. It is not clear whether social interaction leads to the decentration necessary to benefit from collaboration, or that decentration has to happen before genuine collaboration can take place. Other research suggests that developmental factors need to be taken into account in resolving this issue. Azmitia (1988) looked at pairs of 5 year old with equivalent general abilities and found that when novices (with respect to the domain) were paired with experts on a model building task they improved significantly, whilst equal ability pairs did not. Azmitia argues that pre-schoolers may lack the skill to sustain discussions of alternative hypotheses.

Vygotskian theory does not place the same sort of explicit developmental constraints on the ability to benefit from collaboration, but recent researchers (e.g., Wood et al., in press; Tomasello et al., 1993) have argued that certain skills in understanding other people's mental states are required for this which may set developmental constraints on collaborative learning. With a simple task this may be achievable at around 4 years of age, since children at this age can understand that another may lack the knowledge necessary to perform an action (or misrepresent the situation) and they can predict the state of the other's knowledge. However, with more complex tasks, which demand reasoning using that knowledge to predict the partner's actions on the basis of their belief and intentions may not be achievable until about 6 years. In order to achieve shared understanding in a collaborative activity, the child must also be able to coordinate all these representations and have sufficient skills to communicate with respect to them.

Research on peer tutoring has identified some conditions which are also relevant to collaborative learning. The first condition is that the child-tutor must be skilled at the task. Radziszewska and Rogoff (reported in Rogoff, 1990) found that training a 9 year old peer to the same level of performance as an adult on a planning task led to peer dyads performing as well as adult-child dyads and better than peer dyads in which neither partner had been trained. A second pre-requisite is the ability of the child to reflect upon his or her own performance with respect to the task. Thirdly, in order to tutor contingently (i.e., to monitor the effects of previous help on subsequent actions by the learner), the child has to be able to assess whether the learner's action was wrong with respect to the instructions or wrong with respect to the task, and then be able to produce the next tutorial action on the basis of both a representation of the previous instruction and an evaluation of the learner's response to that instruction. Ellis and Rogoff (1982) found that 6 year old children were relatively unskilled at contingent instruction compared with adult tutors. Wood et al. (in press) found that 5 year old peer tutors were similarly unskilled relative to 7 year old tutors, and that 5 year olds tended to have difficulty inhibiting their own actions sufficiently to allow their "tutee" to learn the task. However, children at this age were better "collaborators" than 3 year old comparison dyads.

3.2.3 Task features

Tasks that have been typically used in collaborative learning from a Vygotskian perspective include skill acquisition, joint planning, categorisation and memory tasks. In contrast, the implication from socio-cognitive theory is that tasks should promote differences in perspectives or solutions. Typically, conservation and coordination tasks involve perspective-taking, planning and problem solving. There is thus little overlap in the nature of tasks investigated from the Piagetian and Vygotskian perspective. It is also clear that the nature of the task influences the results: one cannot observe conceptual change if the task is purely procedural and does not involve much understanding; reciprocally one cannot observe an improvement of regulation skills if the task requires no planning. Some tasks are less "shareable" than others. For instance, solving anagrams can hardly be done collaboratively because it involves perceptual processes which are not easy to verbalise (if they are open to introspection at all). In contrast, some tasks are inherently distributed, either geographically (e.g., two radar-agents, receiving different data about the same aeroplane), functionally (e.g., the pilot and the air traffic controller) or temporally (e.g., the take-off agent and the landing-agent) (Durfee et al., 1989).

3.2.5 Interactions between variables

Researchers rapidly discovered that the independent variables we have described so far do not have simple effects on learning outcomes but interact with each other in a complex way. Let us for instance examine the interaction between the composition of the pair and the task features. Studies that have compared the relative benefits of interacting with adults versus interacting with peers suggest that they vary according to the nature of the task, with peers being more useful than adults in tasks which require discussion of issues. Adult-child interaction may be more controlled by the adult rather than being a reciprocal relationship. Children are more likely to justify their assertions with peers than with adults. Rogoff (1990) notes that the differences between socio-cognitive and socio-cultural approaches with respect to composition of dyads are reconcilable. As she points out, whilst Vygotsky focused on acquiring understanding and skills, Piaget emphasised changes in perspectives or restructuring of concepts. Tutoring or guidance may be necessary for the former, whilst collaboration between peers of equivalent intellectual ability may be better in fostering the latter (Damon, 1984). So, how dyads or groups should be composed with respect to skills and abilities may depend upon what learning outcomes one is interested in (e.g., skill acquisition vs. conceptual change) and what tasks are involved (e.g., acquiring new knowledge versus restructuring existing knowledge).

Although few studies have involved a direct comparison of peer collaboration and peer tutoring with the same task, the type of task may interact with the developmental level of the learner and the nature of the dyad. For example, Rogoff (1990) argues that planning tasks may be difficult for very young children because they require reference to things which are not in the "here-and-now". However, adults may be able to carry out such metacognitive or metamnemonic roles that are beyond children, whilst demonstrating to the child how such processing could be accomplished. So, certain types of task may have inherent processing constraints which in turn place constraints on how the interaction should be supported.

3.3 The "interactions" paradigm

The complexity of the findings collected in the second paradigm led to the emergence of a third one. This introduces intermediate variables that describe the interactions that occur during collaboration. The question "under which conditions is collaborative learning efficient?" is split into two (hopefully simpler) sub-questions: which interactions occur under which conditions and what effects do these interactions have. The key is to find relevant intermediate variables, i.e., variables that describe the interactions and that can be empirically and theoretically related to the conditions of learning and to learning outcomes. This methodology however raises interpretation difficulties: if some types of interactions are positively correlated with task achievement, it may be that such interactions influence achievement or, conversely that high achievers are the only subjects able to engage these type of interaction (Webb, 1991). Nevertheless, underlying this approach is a fundamental shift: it may be time to stop looking for general effects of collaboration (e.g., in global developmental terms) and focus instead on more specific effects, paying attention to the more microgenetic features of the interaction. We will illustrate this viewpoint by two examples that are important both in psychology and in DAI: explanation and control.

3.3.1 Explanation

One way of describing interactions is to assess how elaborated is the help provided by one learner to the other. This level of elaboration can be considered as a continuum which goes from just giving the right answer to providing a detailed explanation. Webb (1991) performed a meta-analysis of the research conducted on this issue. This synthesis lead to two interesting results: elaborated explanations are not related to the explainee's performance, but they are positively correlated with the explainer's performance. Webb explains the first result by the fact that learning from receiving explanations is submitted to several conditions which may not be watched by the explainer, e.g., the fact the information must be delivered when the peer needs it, that the peer must understand it and must have the opportunity to us to solve the problem. The second result, the explainer's benefit, has been observed by other scholars (Bargh and Schul, 1980). Similar effects (called the self-explanation effect) have been observed when a learner is forced to explain an example to himself (Chi, Bassok, Lewis, Reimann & Glaser, 1989). A computational model of the self-explanation process have been proposed by VanLehn & Jones (1993). The main principle is that the instantiation of general knowledge with particular instances creates more specific knowledge, a mechanism that has also been studied in machine learning under the label 'explanation-based learning' (Mitchell et al., 1986). It would nevertheless be a mistake to consider self-explanation and explanation to somebody else as identical mechanisms. This would dramatically underestimate the role that the receiver plays in the elaboration of the explanation. As we will see in section 5, an explanation is not a message simply delivered by one peer to the other, but the result of joint attempts to understand each other. Webb (1991) found that non-elaborated help (e.g., providing the answer) is not correlated with the explainer's performance and is negatively correlated with the explainee's performance in the case where the explainee actually asked for a more elaborated explanation. Webb explains these results by the fact that providing the answer while the student is expecting an explanation does not help him or her to understand the strategy, and may lead the explainee to infer an incorrect strategy or to lose his or her motivation to understand the strategy.

These findings partially answer the second sub-question of this paradigm, the relationship between categories of interaction and learning outcomes. The first sub-question concerns the conditions in which each category of interaction is more likely to occur. Webb (1991) reviewed several independent variables concerning group composition, namely, the gender of group members, their degree of introversion or extraversion and their absolute or relative expertise. With respect to the latter, explanations are more frequent when the group is moderately heterogeneous (high ability and medium ability students or medium ability and low ability students) and when the group is homogeneously composed of medium ability students. Some other group compositions are detrimental to the quality of explanations: homogeneous high ability students (because they assume they all know how to solve the problem), homogeneous low ability groups (because nobody can help) and heterogeneous groups comprising high, medium and low ability (because medium ability students seem to be almost excluded from interactions).

Verba and Winnykamen (1992) studied the relationship between categories of interactions and two independent variables: the general level of ability and the specific level of expertise. In pairs where the high ability child was the domain expert and the low ability child the novice, the interaction was characterised by tutoring or guidance from the high ability child. In pairs where the high ability child was the novice and the low ability child the expert, the interaction involved more collaboration and joint construction.

3.3.2 Control

Rogoff (1990, 1991) conducted various experiments in which children solved a spatial planning task with adults or with more skilled peers. She measured the performance of children in a post-test performed without help. Overall she found better results with adult-child than with child-child pairs but, more interestingly, she identified an intermediate variable which explains these variations. Effective adults involved the child in an explicit decision making process, while skilled peers tended to dominate the decision making. This was confirmed by the children who collaborated with an adult; those who scored better in the post-test were those for which the adults made the problem solving strategy explicit. These results are slightly biased by the fact that the proposed task (planning) is typically a task in which metaknowledge plays the central role. A socio-cultural interpretation would be that the explication of the problem solving strategy provides the opportunity to observe and potentially internalise the partner's strategy. From a socially shared cognition viewpoint, one could say that making the strategy explicit is the only way to participate in each other's strategy and progressively establish a joint strategy.

4 Tools for observing interactions

When collaboration is mediated via a computer system, the design of this system impacts on the collaborative process. This mediation has methodological advantages: the experimenter may have explicit control over some aspects of collaboration (e.g., setting rules for turn taking, determining the division of labour or distribution of activities). The effects of the computer as medium also has pedagogical aspects: to support the type of interactions that are expected to promote learning. We describe three settings in which the computer influences collaboration..

4.1 Two human users collaborate on a computer-based task

Until relatively recently, one of the main advantages associated with computer use in schools was seen in terms of the potential for individualised learning. However, since schools generally have more students than computers, children often work in groups at the computer. Several empirical results suggest that group work — at least dyadic work — at the computer may enhance the benefit derived from the collaborative learning situation (for a review, see Blaye et al, 1990). The specific questions to be addressed here deal with the extent to which learner(s)-computer interaction and human-human interaction can reciprocally enhance one another. For instance, interfaces which induce a specific distribution of roles between learning partners help to foster social interaction (O'Malley, 1992; Blaye et al., 1991). Such interfaces can serve to scaffold the executive and regulative aspects of the collaborative task. Another interesting example concerns the principle of immediate feedback which was seen as a critical feature in the first generation of educational software. It seems that immediate feedback may prevent fruitful exchanges between human co-learners because they then rely on the system to test their hypotheses instead of developing arguments to convince one another (Fraisse, 1987). In other words, aspects of the software can modify the socio-cognitive dynamics between the learning partners. In particular, the computerised learning environment constitutes in itself a mediational resource which can contribute to create a shared referent between the social partners (Roschelle & Teasley, in press).

This research does not aim to build a ‘theory' of human-human collaboration at the computer. The fact that the medium (i.e., the computer) is similar is by no means a sufficient reason to unify this field of research. Different interfaces, different computer-based tasks and activities may yield very different interactions and learning outcomes. However, for the sake of simplicity, we refer generically to computer-based activities in order to discuss the other general parameters which exert an influence (e.g., frequency of feedback, representations induced by the interface, role distribution, etc.).

4.2 Computer-mediated collaboration

While the previous setting was influenced by research in educational technology, the setting considered here has developed in parallel with work on 'computer-supported cooperative work' (CSCW). This discipline covers communication systems from simple electronic mail to more advanced ‘groupware’ (Shrage, 1992). There are various ways in which computers can support communication. In the past, this technology has been restricted to textual communication, but developments in broad bandwidth technology allow for more exciting possibilities such as synchronous shared workspaces and two-way audio-visual communication. Generally speaking, broad bandwidth is expected to afford greater opportunities for collaboration. This does mean that older technologies should be superseded. For instance, asynchronous text-based communication provides time for reflection on messages and allows students lacking in confidence to learn nevertheless by “eavesdropping” on conversations. In addition, low bandwidth communication may have some advantage in that, if it takes time and costs money in terms of connect time and if displays are restricted to a screen at a time, students may be forced to consider their responses more carefully.

Computer-mediated communication settings enables the experimenter to consider the communication bandwidth as factor. For instance, Smith et al. (1991) observed that task distribution was easier with a larger bandwidth (i.e., when seeing each other via video instead of audio-only communication) and when the setting gave users the feeling of being side-by-side, through having a shred workspace. They also observed that establishing face-to-face contact seems to be important during reflection stages, e.g., when partners discuss their observations, hypotheses or strategies. This fits in with research on mediated communication which, in general, suggests that face-to-face communication is more effective than audio-only communication for tasks which involve elements of negotiation (see Short, Williams & Christie, 1976).

4.3 Human-computer collaborative learning

Human-computer collaboration refers to situations where the system and the human user share roughly the same set of actions. We don't include systems which support an asymmetric task distribution, as between a user and a word processor, for instance. We describe two types of system where some learning is supposed to result from collaborative activities: apprenticeship systems and learning environments. Most of these systems do not actually fully satisfy the symmetry criterion.

An apprenticeship system is an expert system that refines its knowledge base by watching a human expert solving problems. The human expert is actually more teaching the system than collaborating with him or her, but the techniques developed are relevant to collaborative learning. The expert's behaviour is recorded as an example and the system applies explanation-based learning (EBL) techniques to learn from this example. In ODISSEUS (Wilkins, 1988), the system attempts to explain each human action in order to improve the HERACLES-NEOMYCIN knowledge base. An explanation is a sequence of metarules that relate the observed action to the problem-solving goal. If ODISSEUS fails to produce the explanation, it tries to "repair" its knowledge base by relaxing the constraints on the explanation process. LEAP (Mitchell et al., 1990) applies a similar approach to the design of VLSI circuits. The user can reject the proposed solution and refine the circuit him or herself. In this case, LEAP attempts to create rules that relate a given problem description to the circuit specified by the expert-user. LEAP explains why the circuit works for the given input signal and then generalises the explanation to create the rule premises. The interesting aspect is that these systems attempt to acquire the metaknowledge used by an expert, a central issue in the Vygotskian approach. However these systems rely on EBL techniques which requires a complete theory of the domain. Human learners theories are rarely complete and consistent. Some research has been carried out to by-pass this problem by integrating EBL with analogical and inductive learning (Tecuci and Kodratoff, 1990).

Not surprisingly, the idea of human-computer collaborative learning has also been applied to educational software. It has firstly been suggested as an alternative technique for student modelling (Self, 1986), then as an attempt to break the computer omniscience that dominates educational computing (Dillenbourg, 1992). An interesting issue concerns the necessity to have a plausible co-learner. Along the continuum of design choices, we can discriminate levels of 'sensitivity'. At the first level, we could imagine an ELIZA-like system which randomly asks questions in order to involve the learner in plausible collaborative activities. Second level systems include a co-worker, i.e., an agent which solves problems during the interaction but which is not learning. For instance, the Integration Kid (Chan & Baskin, 1988) does not learn, but jumps (an the tutor's request) to the next pre-specified knowledge level. At the third level, we have a real co-learner, i.e., a learning algorithm whose outputs are determined by its activities with the world, including its interactions with the human learner (Dillenbourg & Self, 1992). This research has not yet produced enough empirical data to determine whether more sensitive systems are more efficient than less sensitive one.

Another interesting issue to be addressed here is that the phenomena observed in human-human collaboration are repeated in human-computer collaboration.

Salomon (1990) raises an important point in terms of knowing whether human-computer interaction has potential for internalisation similar to human-human conversations. He suggests (Salomon, 1988) that some graphic representations could have this potential. We observed (Dillenbourg, in press) that learners were not very 'tolerant' with the computer: firstly, they had difficulties in accepting that the computerised partner makes silly mistakes, then, when the computer was repeatedly wrong, they stopped making suggestions altogether. The advantage of human-computer collaborative systems for the study of collaboration is that the experimenter can tune several parameters regarding to the pair composition (for instance, the initial knowledge of the co-partner).

5 Tools for analysing interactions

At the present state of research, it is not clear which theoretical perspective is most fruitful for analysing interactions, although incidence of socio-cognitive conflict appears to be limited and restricted largely to Piagetian tasks (Blaye, 1988). However, other researchers have shown that there are benefits in generating discussions of conflicting hypotheses for domains such as physics (e.g., Howe et al., 19??). A number of researchers (e.g., Webb, Ender & Lewis 1986; Blaye, Light, Joiner & Sheldon 1991; Behrend & Resnick 1989) have shown that various interactive measures other than "conflict" have a positive correlation with learning outcomes. It may be, as Mandl & Renkl (1992) suggest, that this uncertainty in the field is due to the fact that the Piagetian and Vygotskian perspectives as they stand are simply too *global* to allow proper explanation of the different results. These authors thus argue that "more local", domain/task-specific theories should be developed. As Barbieri & Light (1992) point out, "[s]tudies in collaborative learning at the computer usually do not go into a detailed analysis of interaction …" (p. 200), despite the fact that it is "… important to analyse the quality of the interaction more closely." (p. 200).

5.1 Analysis categories

Most researchers have generally used quite global categories of analysis grouped according to (at least) the following 'oppositions' : (1) *social / cognitive*, (2) *cognitive / metacognitive*, and (3) *task / communicative* . We briefly discuss each in turn.

With respect to the *social/cognitive* distinction, for example, Nastasi & Clements (1992) distinguish "social conflict" (i.e., not related to the problem, such as "name calling", "criticism", etc.) from "cognitive conflict" (which concerns the task conceptualisation or solution). Only the latter was expected to (and did in fact) have a positive correlation with individual improvement.

In terms of the *cognitive/metacognitive* distinction, Artzt and Armour-Thomas (1992) coded "episodes" such as reading, as cognitive, and understanding, planning and analysing as metacognitive. Several types of episodes such as "exploring" and "verifying" solutions were categorised as cognitive *and* metacognitive. The working hypothesis was that "the most successful groups, in terms of both solving the problem and getting active involvement of all the group members, should be those with the highest percentages of metacognitive behaviors" (Artzt & Armour-Thomas, 1992, p. 165).

The third discrimination is between *task and communicative levels*. The communicative level is when the students are trying to achieve a shared understanding by establishing common referents, by giving "commentaries" whilst performing actions, for example (Barbieri & Light, 1992). Task-level analysis categories include "negotiation" (Barbieri & Light, op. cit.), or more generally "task construction". As with the cognitive/metacognitive distinction, many analysis categories combine both communicative and (extra-communicative) task aspects, which is not surprising since the objective is to study their interrelation. For example, Webb, Ender and Lewis (1986) used analysis categories that combined simple speech act types (e.g., question, inform) with parts of the task decomposition (e.g., knowledge of commands, syntax, etc. in computer programming). In fact, whilst there may exist utterances in dialogue that are purely concerned with managing the interaction (such as managing turn-taking, requesting an utterance to be repeated, etc.), in task-oriented dialogues, most utterances concerning the task also have a communicative dimension — making a relevant contribution to the task communicates to the other that you have understood and are sharing a common focus.

To summarise, researchers distinguish management of communicational and social relations from performance of cognitive and metacognitive aspects of the extra-communicative task. Within these two broad categories, different forms of conflict are identified. There is, however, a more fundamental analytical problem to be solved: if individual cognitive progress is associated with cooperation or collaboration in the interaction, then we need to identify when students are in fact cooperating or collaborating, and when they are not really addressing each other (such as "problem-solving in parallel"). This brings us back to the issue raised in the introduction concerning the theoretical distinction between cooperation and collaboration. But, the question now is: how do we know when students are truly collaborating? Which kind of interactions can be identified as collaborative? In order to address this question, Roschelle and colleagues introduced the notion of a "Joint Problem Space" [JPS], consisting of jointly agreed goals, methods and solutions. At the level of social interaction, in order to determine what is in fact "shared" or "mutually accepted", it was necessary to determine when a "Yes" signalled 'genuine' agreement and when it merely indicated "turn taking" ("I can hear you, go on …", etc.). This latter problem has been extensively studied in linguistics within a general model for *linguistic feedback* (Allwood, Nivre & Ahlsén 1991; Bunt 1989). Thus, the meaning of "yes" in a given dialogue context depends on the preceding speech act (answering "yes" to a yes/no question is different from responding "yes" to a statement) and the polarity of the utterance (answering "yes" to "It is raining" may signal acceptance, whereas "yes" after "It isn't raining" can mean "oh yes it is !" or "yes, I agree that it isn't raining"). More generally, utterances like "yes", "no", "ok" and "mhm" give feedback at the level of perception ("I can hear you"), comprehension ("I can hear and understand you") and agreement/disagreement ("I hear you, understand, and agree"). (The first two of these are generally referred to as “backchannel” responses which serve to facilitate turn-taking.) Deciding on the meaning of these expressions in a given dialogue context is thus quite complex, but necessary if we are to understand when students are really collaborating and co-constructing problem solutions. At present this line of research on the pragmatics of communication remains to be exploited in the field of collaborative learning.

5.2 Conversation models

A promising possibility for collaborative learning research therefore is to exploit selective branches of linguistics research on models of conversation, discourse or dialogue to provide a more principled theoretical framework for analysis. Two types of interaction have been universally referred to in collaborative learning research : *negotiation*, often referred to within the Vygotskian "cooperation" approach as an indicator of joint involvement in task solutions, and *argumentation* , as a possible means for resolving socio-cognitive conflict.

In the remainder of this section we review some research in language sciences and AI which may be relevant to analysing these interactional phenomena in cooperative problem-solving dialogues.

5.2.1 Negotiation

In the context of joint problem-solving, we can view negotiation as a process by which students attempt (more or less overtly or consciously) to attain *agreement* on aspects of the task domain (how to represent the problem, what sub-problem to consider, what methods to use, common referents, etc.), and on certain aspects of the interaction itself (who will do and say what and when). In DAI, "communication protocols" based on negotiation between artificial agents have been developed for resolving resource allocation conflicts (Bond & Gasser, 1988; Rosenschien, 1992). Two main negotiation strategies may be used : (1) mutual adjustment, or refinement of the positions of each agent, and (2) competitive argumentation (Sycara 1988,1989), where one agent attempts to convince the other to adopt his proposition. This illustrates the fact that quite specific conditions are necessary in order for negotiation to be used as a strategy: the agents must be able and willing to relax their individual constraints, and the task must possess the required 'latitude' (if the answer is as clear and determinate as "2+2=4", there is no space for negotiation) (Adler et al, 1988). Baker (forthcoming) describes the speech acts and strategies used in collaborative learning dialogues, where a third strategy (other than refinement and argumentation) is "stand pat" — one agent elicits a proposal from the other, using the second agent as a "resource". In other words, we can see at least three different types of negotiation behaviours, where each may be hypothesised to give different learning outcomes: (1) co-constructing problem solutions by mutual refinement, (2) exploring different opposed alternatives in argumentation, and (3) one student using the other as a resource.

There is, however, another type of negotiation that is common to any verbal interaction, and which takes place at the communicative, rather than the task, level: negotiation of *meaning*. The general idea is that the meaning of utterances in verbal interaction (or at least, the aspect of meaning that plays a determining role) is not something that is fixed by speakers and their utterances, but is rather something to be jointly constructed throughout the interaction by both speakers. This continuous process of adjustment of meaning will be a major determinant of what will be internalised at an individual level. Edmondson (1981) refers to this as "strategic indeterminacy", meaning that negotiation of meaning is not a 'defect' of interaction, but is rather *constitutive* of it to the extent that specific interactive mechanisms exist that allow mutual understanding to emerge. Thus Moeschler (1985) states that "Without negotiation the dialogue is transformed into monologue, the function of the interlocutor being reduced to that of a simple receptor of the message." (Moeschler, 1985, p. 176). For example, if one speaker (S1) makes the utterance "the mass is greater for the red ball", and another (S2) replies "No it isn't", S1 can reply with, "no, no, I wasn't saying it was, it was just wondering", thus negotiating the illocutionary value of the utterance to be a question, rather than an affirmation. We can observe this process of negotiation of meaning most clearly in so called "repair sequences" (misunderstanding becomes an explicit object of discourse), but it is important to note that from the point of view of most linguistics schools concerned with conversation, discourse or dialogue, "negotiation" is not a type of isolated sequence that may occur in a dialogue, it is a process operating throughout *any* dialogue (Roulet, 1992).

Attaining shared understanding of meanings of utterances is a necessary condition for collaborative activity (one cannot be said to be 'really' collaborating, or agreed, if one doesn't understand what one is collaborating or agreed about), and as such the collaborative activity determines the *degree* to which 'full' or 'complete' mutual understanding needs to be attained. From a cognitive perspective, Clark & Shaefer (1989) have expressed this fact in terms of the speakers' adherence to a criterion of "grounding" : "The contributor and the partners mutually believe that the partners have understood what the contributor meant to a criterion sufficient for current purposes" (Clark & Schaefer, ibid., p. 262). Speakers do this by generating units of conversation called "contributions". "Contributions" have two phases: a presentation phase and an acceptance phase. They are recursive structures in that each acceptance is itself a new presentation, which the hearer is invited to consider. In acceptance phases, speakers provide *evidence of continued understanding*, to a greater or lesser degree. The recursion terminates when evidence has been provided of the weakest form sufficient for current purposes at a given level of embedding. Types of evidence provided are conditional on the adjacency pair which constitutes a contribution. They include *continued attention, initiation of the relevant next contribution*, *acknowledgement* (feedback or backchannels such as nods, or utterances such as "uh-huh", "yeah", etc.), *demonstration* (hearer demonstrates all or part of what he has understood A to mean), and *display* (hearer displays verbatim all or part of speaker's presentation). Contributions may be generated in one of a number of *contribution patterns,* such as "contributions by turns", by "episodes" (corresponding to the "stand pat" negotiation strategy, described above), and by collaborative completion of utterances. The latter pattern is an indicator *par excellence* of collaboration in verbal interactions.

Krauss and Fussell (1991) observed that, during social grounding, the expressions used to refer to objects tend to be progressively abbreviated (provided that the partner confirms his or her understanding in the abbreviation process). Interestingly, the same phenomena of abbreviation is observed during internalisation (Kozulin, 1990; Wertsch, 1979, 1991), i.e., as the difference between social and inner speech. This difference is due to the fact that "inner speech is just the ultimate point in the continuum of communicative conditions judged by the degree of 'intimacy' between the addresser and addressee" (Kozulin, 1990, p. 178). These similarities between social grounding and internalisation fit with the 'distributed cognition' view that questions the arbitrary boundary between the social and the individual. As thinking is described as a language with oneself (Piaget, 1928; Vygotsky, 1978), internalisation may be the process of grounding symbols with oneself.

We can ask whether similar grounding mechanisms also occur in human-computer collaboration. Some experiments with MEMOLAB (Dillenbourg et al., 1993) revealed mechanisms of human-computer grounding: the learner perceives how the system understands him and reacts in order to correct eventual misdiagnosis. Even in DAI, authors start to emphasise the need for each agent to model each other (Bird, 1993) and exchange self-descriptions (Gasser, 1991).

Turning finally to argumentation, we noted above that it is one of the strategies which may be used in collaborative interactions. As such, the way in which conflict or disagreement may be resolved in an ensuing argumentation phase may be strongly influenced by the context of the higher level goal of achieving agreement. For example, students often take the “least line of resistance" in argumentation, shifting focus to some minor point on which they have agreed, and thus never "really" resolving the conflict (Baker 1991). This may be related to the following question posed by Mevarech and Light (1992, p. 276): "Is conflict itself sufficient as an "active ingredient", or is it the co-constructed *resolution* of such conflict which is effective ?". It therefore seems clear that detailed analysis of argumentations in collaborative dialogues may help to give finer-grained indications for explaining some experimental results. At present, little research has been done on this (but see Trognon & Retornaz, 1990; Resnick et al, 1991), and a vast literature on argumentation in language sciences remains to be exploited (this is not the place to review such a literature, but see for example Toulmin, 1958; Barth & Krabbe, 1982; van Eemeren & Grootendorst, 1984; Voss et al., 1986; Miller, 1987).

6. Synthesis

Collaboration is not simply a treatment which has positive effects on participants. Collaboration is a social structure in which two or more people interact with each other and, in some circumstances, some types of interaction occur that have a positive effect. The conclusion of this chapter could therefore be that we should stop using the word 'collaboration' in general and start referring only to precise categories of interactions. The work of Webb, reported above, showed that even categories such as 'explanation' are too large to be related to learning outcomes. We have to study and understand the mechanisms of negotiation to a much greater depth than we have so far.

We do not claim that conversational processes are exclusive candidates for explaining the effects observed. The 'mere presence' of a partner can, in itself, be responsible for individual progress. Neither should we discard the role of non-verbal communication in collaboration. However, verbal interactions probably provide, at present, more tractable ways in which to tackle the development of computational models of collaborative learning.

In various areas of cognitive science psychologists and computer scientists have developed computational models together. This is not the case for collaborative learning. We hope that this chapter will help psychologists and researchers in machine learning to develop models of collaborative learning. Both in psychology and in computer science, individual learning and verbal interactions have been studied separately. The challenge is to build a model for how the two interrelate, for how dialogue is used as a means for carrying out joint problem-solving and how engaging in various interactions may change the beliefs of the agents involved.

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