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Interactions between children's metacognitive abilities, working memory capacity, strategies and performance during problem-solving

David Whitebread
Homerton College, Cambridge, U.K.

This paper reports two related studies intended to explore the interactions between children's metacognitive abilities, their working memory capacity, the development and selection of strategies and their performance on problem-solving tasks. In the first study, a sample of 20 children aged 5 and 6 were presented with a reclassification task. In the second study, a sample of 72 children aged 6, 8 and 10 were presented with a multidimensional discrimination learning (MDL) task. Data was collected related to the children's metacognitive abilities, working memory capacity, response strategies and task performance. The results indicated that performance on both tasks was dependent upon developmentally changing interactions between these various aspects of cognitive functioning. In particular, the relationship of working memory capacity to performance was dependent upon metacognitive abilities. The results also suggested that metacognitive awareness did not directly affect performance, but that such a relationship was dependent upon the development of strategic control. The implications of these results for understanding U-shaped behavioural growth and other common developmental patterns are discussed. Within the educational sphere, the study emphasises the significance and possibility for children as learners of fostering certain kinds of metacognitive ability.

Introduction

Within education there is increasing awareness of the importance of helping children to develop their abilities as active problem-solvers. The research reported in this paper was intended to explore the interactions between different aspects of children's metacognitive abilities, their working memory capacity, their construction and selection of strategies and their performance on problem-solving tasks.

Historically, various aspects of cognitive processing have been advanced as the key factor explaining the development of children's learning and problem-solving abilities. Brainerd (1983), for example, prefaced a comprehensive review of work on "working memory systems" by the claim that "cognitive development can, in fact, be reduced to memory development".

The work of Kyllonen and Christal (1990) is an example of a number of studies which have subsequently attempted to establish that children's developing abilities to reason and solve problems is largely a consequence of the growth of their working memory capacity.

Following the seminal work of John Flavell and his collaborators (Flavell, 1979; Flavell, Beach, & Chinsky, 1966), however, others have attempted to establish the pre-eminent role of metacognition in children's developing abilities to think and learn. Brown (1987), for example, asserted the view that "metacognitive-like concepts lie at the very roots of the learning process".

The research reported in this paper was inspired by the view that little more could be learnt, however, by attempting to establish a single most important factor in children's cognitive development. On the contrary, it is argued that our understanding of the development of children's cognitive abilities will be best advanced at this time by analysis of the ways in which different elements of cognitive functioning interact. A growing amount of research in recent years has moved towards this view. Following the work of such as Siegler and Jenkins (1989), problem-solving performance has been increasingly characterised as dependent upon the construction and selection of cognitive strategies, which is, in turn, dependent upon interactions between different cognitive and metacognitive processes. Both the working memory demands of a task and children's metacognitive abilities have been shown to influence strategy selection and children's consequent performance on problem-solving tasks (Bjorklund, 1990; Scardamalia, 1977; Schneider & Weinert, 1990). A growing consensus has emerged that while the development of working memory capacity might be necessary to enable children to carry out more and more complex strategies, the construction of new strategies and the appropriate selection of strategies in relation to any particular task are more likely to be the product of metacognitive processes and abilities (Roberts & Erdos, 1993).

Other researchers have pointed out that metacognitive processes in themselves may well occupy working memory space, and so interactions between these elements would be expected during strategy construction, selection and execution (Shatz, 1978). Metacognitive processes can only occur, according to this view, when all of an individual's working memory capacity is not taken up by carrying out the actual task. Brown and DeLoache (1978) developed this into a general model of learning both developmentally and within any task. They suggested that the novice on any task will initially show little or no "intelligent self-regulation". Then, as the task and its subprocesses become more familiar, as Case (1985) has subsequently demonstrated, processes of automatisation lead to the freeing up of working memory capacity, and an increasingly metacognitively active period of monitoring and self-regulation. Finally, as the necessary subprocesses and their co-ordination become overlearned, expertise is achieved and performance on the task becomes relatively automatic.

Metacognition itself, of course, is not a unitary process, but contains many aspects and elements, each of which contribute to cognitive functioning and development in different ways, and a number of which may themselves interact with each other. Flavell's (1979) original distinction between metacognitive knowledge and metacognitive experience has proved consistently helpful in subsequent research and analysis. Early attempts to link children's general level of metacognitive knowledge with their abilities on any particular task, for example, were disappointing. Following analyses by Brown (1987) and others, however, metacognitive knowledge about particular tasks derived from direct experience has been found to be much more closely related to performance. In relation to metacognitive experience as such, Brown (1978), in an earlier detailed analysis of the necessary components of a metacognitive system, established the distinction between a monitoring and a control function. These are referred to by her as "metacomprehension" and "insight". It has been suggested that metacomprehension, or an individual's knowledge about their own state of knowledge in relation to any particular task, may be a necessary but not sufficient condition for the construction and appropriate selection of strategies (Nisbet & Shucksmith, 1986). On the other hand, insight, or strategic control, the ability to change the employment of a strategy when it is more or less appropriate, has been shown to be dependent upon monitoring and metacomprehension, but possibly more directly related to successful problem-solving (Roberts & Erdos, 1993).

These kinds of interactions between different elements within cognitive processing may well account for a number of commonly observed developmental patterns. It seems likely that as children's learning and problem-solving abilities develop the pattern of interactions between the various metacognitive abilities, working memory capacity, strategy and performance will change. For example, Siegler (1997) has recently described cognitive development as a series of overlapping wave patterns (as opposed to the step-like nature of earlier models involving "stages" of development). An interactive developmental model is more likely to be able to account for this. Other examples of developmental patterns more likely to be explained by an interactive model would be U-shaped behavioural growth (Strauss & Stavy, 1982) and the increasingly closer relationship with age commonly reported between aspects of metacognition and performance (Schneider & Weinert, 1989).

This paper reports two related studies using a Reclassification and a Multidimensional Discrimination Learning (MDL) task, intended to explore the developmental patterns of interactions between children's metacognitive abilities, their working memory capacity, the selection of strategies and their performance on problem-solving tasks. The tasks used in the two studies were selected as a result of two general considerations. First, they both tap into central cognitive processes within children's learning. Reclassification was a task designed by Piaget as an early example of the child's developing "flexibility in hindsight and foresight", or what we would now refer to as the ability to reflect upon and make predictions about experience (Inhelder & Piaget, 1964). The MDL task, originally devised and explored by Bruner, Goodnow and Austin (1956), involves the fundamental learning mechanism of inductive reasoning. The central significance of processes of inductive reasoning within human learning have been well argued by Holyoak and Nisbett (1988) and by Glaser and Pellegrino (1987).

Second, both tasks have been analysed in terms of the strategies which children generate in order to solve them. However, the construction and selection of these strategies have not been analysed in terms of their relation to the development of working memory capacity and metacognitive abilities.

The Reclassification task is a much simpler task than the MDL task. Only two clear strategic approaches have been identified in the literature, whereas many more have been identified for the MDL task (five different strategic levels were identified in the current research). Children achieve near perfect performance on the Reclassification task at a much earlier age than on the MDL task. The Reclassification task was therefore used in the first study reported here, which was intended as a simple initial exploration of relations between working memory capacity, metacognitive knowledge derived from direct experience of the task, strategy and performance.

This first study was directed at the following questions. Was successful performance on the Reclassification task related to working memory capacity, or to metacognitive abilities alone? Or were there significant interactions between these aspects of cognitive functioning? How did the use of different strategies relate to working memory capacity and metacognitive abilities? Were relationships consistent across age groups, or were there developmentally distinct patterns of interactions of the kinds predicted by some of the various models discussed above?

Study 1: Reclassification task

Methodology and research design

Sample. The first study was carried out in an averagely sized Leicestershire Primary school with a socially mixed catchment area. An initial sample of 24 children aged 5 and 6 years was used, with 12 children in each age group. In order to establish matched groups across the age groups, however, the final analysis used the results of 10 children in each age group. These groups were matched for metacognitive ability (in each age group 5 children were successful on the metacognition test and 5 unsuccessful) and for working memory capacity (the total score on the digit span task for the ten 5 year olds was 41 and for the ten 6 year olds was 43).

The Reclassification task. The children were presented with a reclassification task, based upon that devised by Inhelder and Piaget (1964). The task was introduced to the children as a game with three sets of eight identical plastic logic blocks (containing two values of three dimensions) and three dolls. The child was asked to help each doll sort the blocks into two pots so that each doll did it a different way.

When they had successfully achieved this the experimental task involved sorting into two pots sets of eight picture cards which, like the logic blocks, contained two values of three dimensions (e.g., man or house, red or blue, large or small). Having sorted the picture cards once in this way, the child was then asked to re-sort them another way on two further occasions. The one significant difference of the experimental task from the introductory task was that the cards were smaller than the logic blocks and designed to lie flat in the sorting pots, one on top of the other. This meant that, whereas in the introductory task the children could refer back to the previous sorts, in the experimental task they had to rely on their memory of them because the only cards they could see were the top ones in each pot.

Verbal prompts were offered where the child reproduced an earlier dichotomy, or produced an incorrect or jumbled sort, or failed to sort into the two pots at all. Only one verbal prompt was offered on each sort. These prompts consisted of simple reminders of the rules of the game. Two versions of the task were used, a high saliency version using objects familiar to young children and a low saliency version using abstract designs (see Figure 1).

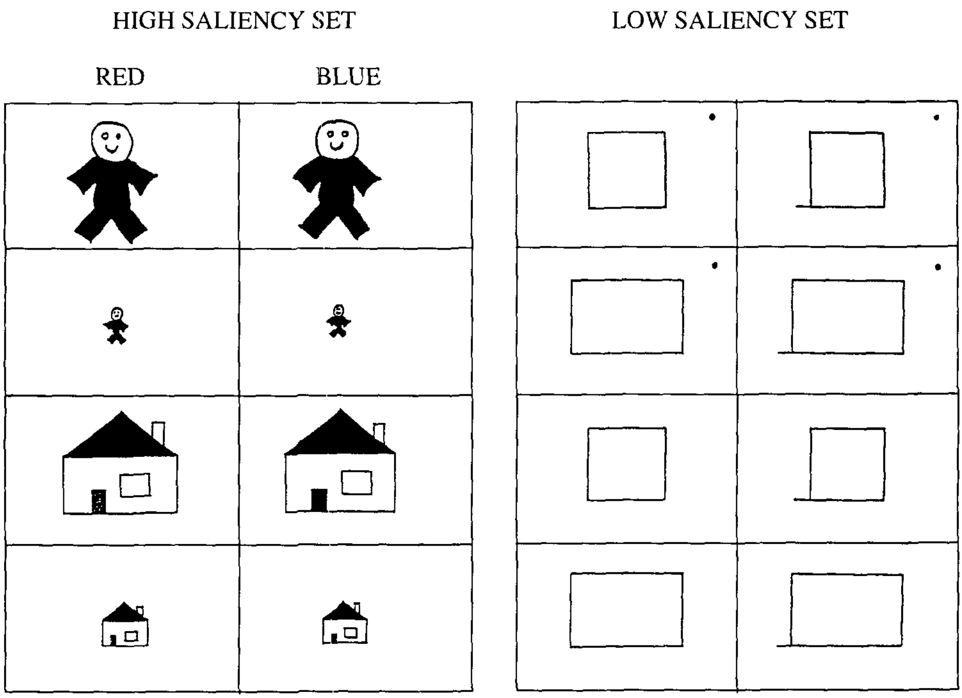

Figure 1. Picture cards used in reclassification task

Strategies and performance. The children's response strategies and performance were analysed for the task. Two alternative strategic approaches were examined and identified by simple observation of the children's actions and verbal "commentaries". These strategies had been identified by Inhelder and Piaget (1964) and referred to as "ascending" and "descending" strategies, which they described thus:

"Using an 'ascending' method means starting out with a multiplicity of sub-collections corresponding to the lowest rank of an ordered classification, and then combining them step-by-step until one reaches one or more possible dichotomies. Using a 'descending' method means starting from a more general classification which may well take the form of a broad dichotomy, and then subdividing these classes in terms of further dichotomies" (Inhelder & Piaget, 1964, p. 212).

Performance on the reclassification task was assessed in terms of the children's success at performing successful sorts, either with or without verbal prompts. For each sort 2 points were awarded where it was correct and unprompted, 1 point where it was correct but had been assisted by a verbal prompt, and no points where it was still incorrect even after a verbal prompt.

Metacognitive awareness and knowledge of the task. The children were assessed for the metacognitive knowledge based upon their direct experience of the task. This assessment used a production task based on that devised in relation to the oddity problem by Lunzer (1968). He demonstrated that children's ability to construct their own oddity problem was closely related to their metacognitive awareness of the task. Here the production task consisted of asking the child to produce a simpler set of four pictures (e.g., blue or red, square or circle) but of the same logical type as the picture cards used in the experimental task, i.e., four different pictures. Each child was given two opportunities to successfully produce such a set of cards. If they were successful on either occasion they were classified as "metacognitively aware". If they were unsuccessful on both occasions they were classified as "metacognitively unaware".

Working memory capacity. Working memory capacities were assessed using a digit span test of the kind used by Halford (1980) in his study of the relationship between short-term memory span and the ability to cross-classify in a matrix problem. The children were read six series of 2 digits, then six series of 3 digits and so on, until they failed correctly to repeat at least three series out of six, at which point the test was ended. The score was taken as the longest series upon which they correctly repeated at least three series.

Results

The results from this first study indicated that performance on the reclassification task was dependent upon interactions between the children's metacognitive awareness and knowledge of the task, their working memory capacity and the strategy they adopted. The pattern of relationships between these different cognitive elements and performance was markedly different, however, between the 5 year olds and the 6 year olds.

As Inhelder and Piaget (1964) had originally found, many children in the present study used a mixture of the two strategies. However, there was some evidence of a developmental shift in strategy, with three of the 6 year olds systematically adopting the more sophisticated "descending" strategy, as opposed to only one of the 5 year olds. There was also evidence to suggest that the metacognitively aware children were more likely to use this strategy (again a difference of 3 to 1) while the metacognitively unaware children were more likely to use the simpler "ascending" strategy (a difference of 4 to 2).

There was not a simple relationship, however, between either metacognitive awareness or working memory capacity and successful performance on the reclassification task. Table 1 reports the correlations between scores on the metacognitive awareness and reclassification tasks for the whole sample and the 5 and 6 year olds separately.

Table 1

Correlations of scores on Metacognition task and Reclassification task

Task type	Whole sample	5 year olds	6 year olds
High saliency	.24	-.08	.52
Low saliency	.24	-.12	.60
All tasks	.25	-.11	.58

As can be seen, the results for the two age groups are dramatically different. For the 5 year olds there was no relationship between metacognitive awareness and performance on the Reclassification task, but for the 6 year olds there was a reasonably strong relationship. This interaction with age suggests that very different cognitive dynamics, probably involving processes of strategy choice, were highly significant between the two age groups and this view was confirmed when the relationships between working memory capacity, metacognition and performance were examined, as reported in Table 2.

Table 2

Correlations of scores on Digital Span test and Reclassification task

Task type	Whole sample	5 year olds	6 year olds	Metacognitive unaware	Metacognitive aware
High saliency	.37	.23	.45	.74	.03
Low saliency	.36	-.11	.70	.52	.12
All tasks	.38	.04	.61	.60	.09

Once again, no relationship existed for the 5 year olds between working memory capacity (as measured by the test of digital span) and performance on the Reclassification task, while a strong relationship did exist for the 6 year olds.

These two results for metacognition and working memory capacity together suggest a transformation in cognitive dynamics between the two age groups. The 6 year olds appeared to be struggling to understand the logic of the Reclassification task and attempting to carry out a planned strategy. Their success was dependent, on the one hand, on the extent to which their metacognitive knowledge and monitoring enabled them to choose an effective strategy and, on the other hand, the extent to which their working memory capacity allowed them to carry out their chosen plan. The 5 year olds, however, appeared to be adopting a less consistent, more trial and error and haphazard approach.

The other results reported in Table 2 further support a model whereby metacognitive awareness and working memory capacity are seen to interact with strategy choice and task performance. Thus, while performance on the Reclassification task was unrelated to working memory capacity for the metacognitively aware children, there was a strong relationship for the metacognitively unaware. The clear implication is that for the metacognitively unaware children, who tended to adopt the less efficient "ascending" strategy, greater demands were made of their working memory capacities. For these children, as a consequence, performance on the task was strongly associated with their ability to hold information in working memory. The metacognitively aware children, however, tended to adopt the more efficient "descending" strategy which did not make such demands. Consequently, for these children performance on the task was completely unrelated to working memory capacity.

Discussion

Very clear answers emerged, therefore, from this first study to the questions posed. Where successful performance on the Reclassification task was related to working memory capacity or to metacognitive knowledge based upon experience of the task (almost exclusively amongst the 6 year olds), there were highly significant interactions between these aspects of cognitive functioning. The results were also consistent with a model suggesting that working memory capacity was related to the ability to carry out a chosen strategy, while metacognitive awareness was related to making an appropriate strategy choice. Developmentally distinct patterns of interactions also clearly emerged, as the pattern of relationships for 5 year olds was very different from that for the 6 year olds.

While these results were intriguing, however, the small size of the study and the rather simple measures of the various cognitive elements used clearly limited their generalisability. A second study was, therefore, constructed which used a larger sample and a more sophisticated task allowing the questions addressed in the Reclassification study to be explored more thoroughly. The MDL task used, as we have indicated earlier, allows more strategic variability. Both working memory capacity and metacognitive abilities were measured and analysed in more detail. As a consequence of the more challenging nature of the task, development of performance could be analysed across a wider age span allowing for the possibility of more sophisticated developmental patterns to emerge.

As well as providing further and possibly stronger evidence in relation to the original questions to which the Reclassification study was addressed, this second study with the MDL task was able to deal with two further questions. First, whether the kinds of relationships and developmental patterns found in the first study were merely an artefact of the particular task and age groups studied, or whether the results would be similar with a second task and over a wider age range. Second, the analysis of different components of children's metacognitive experience allowed the exploration of ways in which particular metacognitive processes and abilities affected the processes of strategy construction and choice during problem solving.

Study 2: Multidimensional Discrimination Learning Task

Methodology and research design

Sample. The second study was carried out with a sample of 72 Leicestershire Primary school children, comprising three equal groups of 24 children aged six, eight and ten years old. The children were sampled equally from two large village schools which together drew their children from across the social spectrum. Within each age subgroup half were drawn from each school, and within each of these age/school subgroups of 12 children, half were girls and half boys.

Multidimensional discrimination learning task. The MDL task used in the study was directly based upon a version developed by Kemler (1978), which presents the problem within a story-and-game context. The task was presented to the children as a game within which they had to identify one of two identical twins (Anna and Sally), who are forever exchanging their clothes. The twins have agreed that, for purposes of identification, each day there will be one item of clothing (known only to themselves and their teacher) which they do not exchange. This item of clothing is the twin's "secret" and that is what the children had to discover. Specifically, they had to discover which item Anna was always wearing on that day, and never exchanged with her sister.

Each one of the stimuli presented to the children consisted of a 5 in. x 8 in. line drawing of a young girl portrayed from the knees to the top of the head. The differences between stimuli were introduced by elaborating the basic form with variable kinds of clothing. These clothing items consisted of two variations for each of eight clothing attributes or "dimensions". In each problem set, which represented a new school day, a selection of four of the eight clothing "dimensions" was used (see Figure 2).

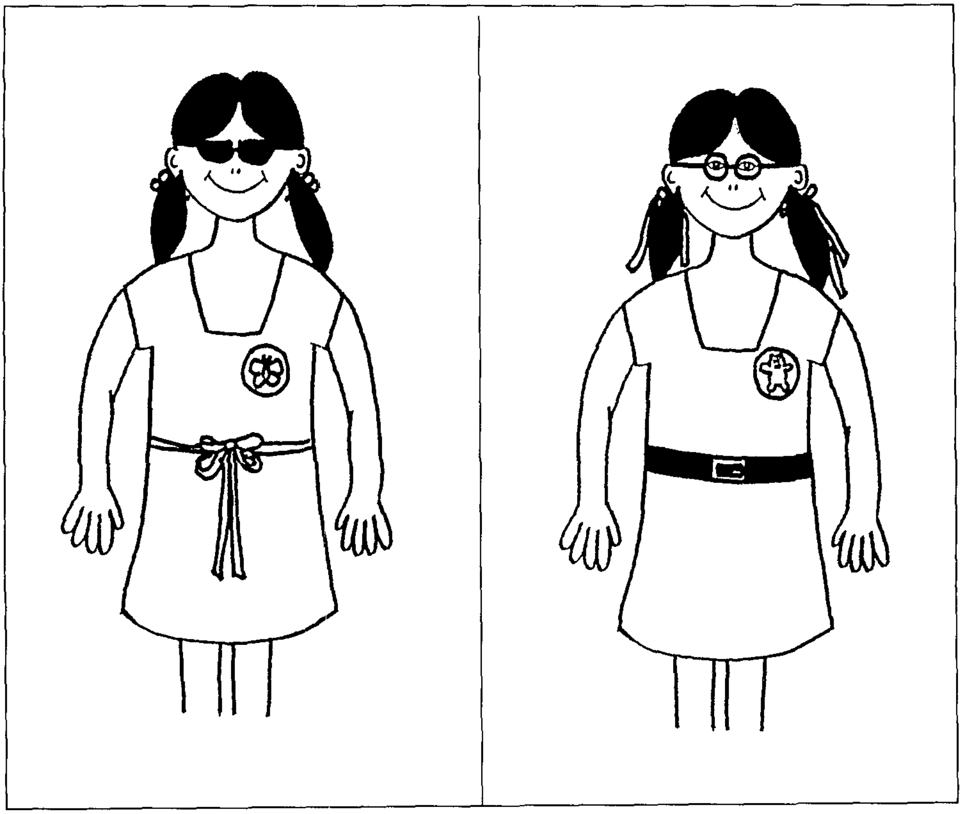

Figure 2. Picture cards for Multidimensional Discrimination Learning task (In this example problem relevant "dimensions" are glasses, hair fastenings, badges and belts)

The procedures adopted for pre-training and the experimental problems followed closely those reported in detail by Kemler (1978), but with some variations. Her pre-training procedure of demonstrating the girls exchanging clothing items using blank cards and clothing "cut-outs" was used. However, in the light of the findings of Bryant and Trabasso (1971) and many others, indicating improvement in children's performance when they are allowed time to become thoroughly familiar with the task materials, this pre-training was preceded by a memory task (see below), using the cut-out clothing items. As part of this task, the children were asked to name the clothing items, and whatever name they supplied was then used throughout the rest of the procedure.

Each child attempted to solve six experimental problems, each of which consisted of a maximum of 16 trials. Two of these problems were of the standard form, where the twins were wearing just the four relevant clothing dimensions and the child was shown both twins on each trial. The other four problems were devised to be more difficult based on previous research with the MDL task showing that children have difficulty with irrelevant (Barringer & Gholson, 1980) or negative (Tumblin & Gholson, 1980) information. Thus, in two problems the twins were also wearing identical (and, therefore, irrelevant) clothing items. In the other two problems the child was only shown one card on each trial. This might show a picture of either of the twins (thus obliging the children to use negative information on trials where they were shown "Sally" and not "Anna"). Within each problem the pattern of presentation of the clothing items was standardised to follow the kind of "orthogonal" sequence originally devised by Levine (1966), thus:

	Card 1	Card 2
Trial 1	AAAA	BBBB
Trial 2	AABB	BBAA
Trial 3	ABAB	BABA

At this point, Trial 3 becomes the first of a new orthogonal sequence of three trials. This sequence, repeated throughout the problem presentation, enables the solution to a four-dimensional problem to be defined over any three trials.

Early studies of hypothesis-testing deduced subjects' hypotheses on an MDL task simply from their pattern of choices, using Levine's (1966) blank-trial procedure. More recently, Phillips and Levine (1975) and Kemler (1978) demonstrated that this procedure led to an underestimation of children's problem-solving abilities, and that supplementing this by asking children for verbal "hypotheses" (sometimes referred to as "introtacts") provided a more accurate picture. This procedure was, therefore, adopted within the present study, with the children being asked on each trial which card they thought represented Anna (or for "negative information" type problems which twin the one card shown represented). Feedback was then provided as to whether they had identified Anna correctly, and they were asked what they now thought Anna's "secret" item of clothing might be.

In the vast majority of early studies of discrimination learning and hypothesis testing where participants were asked to verbalise their hypotheses they were only permitted, on any one trial, to verbalise one hypothesis. Phillips and Gholson (1980) recognised that this was a rather artificial constraint, as in the early stages of an MDL problem more than one solution may still be a possibility. They therefore asked participants to indicate "which things could still be correct", and found interesting variations in the number of hypotheses verbalised by different children. Within the present study, therefore, this latter procedure was also adopted. The children were asked to say which clothing items could be Anna's secret today.

On each trial it was recorded which choice of Anna was made and which clothing items were verbalised as possible solutions. The criterion for a problem to be deemed to be solved was that the child had correctly identified Anna on five successive trials (consequently referred to as the "criterion" trials).

Strategies and performance. The inductive reasoning strategies used by the children on the MDL task were analysed using their pattern of choices of "Anna" and their hypotheses on each trial about current possible "secret" items of clothing. From this data ten Strategy Components were identified based on previous analyses of children's and adult's performance on MDL tasks (Gholson, 1980; Gholson, Levine & Phillips, 1972; Kemler, 1978). Cluster analysis of children's scores on these components, using the iterative relocation method devised by Youngman (1976), was used to identify distinct strategic patterns of behaviour in response to the task. Further details of this analysis have been provided in a previous report focusing on this aspect of the MDL study (Whitebread, 1996).

Performance on the MDL task was measured in three ways:

Trial of Last Error (TLE): a score based on the last trial at which an incorrect choice of Anna was made; this is a standard measure of the efficiency with which an MDL problem has been solved used by Kemler (1978) and most other studies.

- *Verbalisation of Correct Hypothesis (VCH)*: a score based on the number of "criterion" trials on which the children verbalised the correct "secret" or hypothesis; it has been commonly reported in the literature that children pass through a stage in which they can choose the correct card or picture, but are unable to verbalise the hypothesis guiding these choices (Spiker & Cantor, 1977).
- *Hypotheses on Trials 1, 2 & 3 (H123)*: a score based on the accuracy of the children's assessment of the number of possible hypotheses on the first three trials of any problem (i.e., four on Trial 1, two on Trial 2 and one on Trial 3); Phillips and Gholson (1980) provided evidence of children's developing ability to recognise accurately the number of hypotheses which were actually still possible solutions after different numbers of trials; this represents the most sophisticated level of performance on the task. Two points were awarded on each trial where the correct number of hypotheses were verbalised and 1 point was awarded where the number verbalised was only one more or less than the accurate number.

In addition, improvement over the 6 problems attempted in each of these aspects of performance was taken as a measure of the children's ability to learn from their experience of the task. *Learning* scores were constructed by deducting scores for the first three problems from those of the second three.

Metacognitive abilities. In this second study the children were assessed for their metacognitive awareness of the task (measured as knowledge of the task based on their direct experience of it), metacomprehension and strategic control.

Metacognitive awareness was assessed in relation to features of the MDL task which had made different versions of the task (standard, negative information, irrelevant dimensions) easier or harder. This was assessed using three questions:

- *Question 1*: the children were shown example cards representing the three problem types as was asked "Which type of problem was easiest?" and "Which type of problem was hardest?". Answers were scored by awarding one point for each correct assessment based upon the child's own performance on the three problem types.
- *Question 2*: the children were shown the blank cards of Anna and Sally and the clothing "cut-outs" used in the pre-training procedure and asked "Can you dress the twins so that it would be easy to find out their secret?" and "Can you dress the twins so that it would be hard to find out their secret?" Answers were scored by awarding points related to the difference in the number of clothing items the child put on the twins in the "hard" and "easy" conditions.
- *Question 3*: the children were shown different sets of cards where 2, 4 and 8 clothing dimensions were relevant to a solution and asked each time "If the twins arrived at school dressed like this, how many times would they need to swap clothes before you could work out their secret?" Answers were scored by comparing the number of swaps suggested for each number of clothing dimensions; one point was awarded for each of the possible comparisons (8v4, 8v2, 4v2) where more swaps were suggested for the higher number of clothing dimensions.

Metacomprehension was assessed by making use of a procedure devised by Berch and Evans (1973). This involved carrying out two further standard MDL problems with each child, but asking them to stop the problem when they were confident that they had found the correct solution. The children indicated their level of confidence by pointing to one of two photographs of a child of their own gender looking either pleased and confident or troubled and unsure. A simple four point scoring system was used reflecting the accuracy with which the child stopped the problem on the first trial on which they could be sure they had the correct solution.

Strategic control was assessed by teaching the children a strategy for solving the standard MDL problem and then seeing whether they were able to abandon it when it became inappropriate, or whether they would blindly follow the rule. The taught strategy involved checking each clothing dimension in turn, starting with the one nearest the top of the picture. It was explained to the children that this was a good strategy because you couldn't get muddled as to which dimensions you had already checked. When they had successfully mastered this procedure they were presented with six problem sets where this was an inappropriate procedure because the twins were wearing identical items for the top two clothing dimensions, which were therefore irrelevant. This was scored on a three point scale: 2 points for an immediate and appropriate strategy change, 1 point for an eventual, appropriate strategy change, and 0 points where the original taught procedure was either strictly adhered to or not consistently replaced throughout the six test problems.

An *overall score for metacognitive abilities* was also computed by adding together the standardised scores for metacognitive awareness, metacomprehension and strategic control.

Working memory capacity. In this study working memory capacity was assessed by means of Pascual-Leone's (1970) Figural Intersections Test (FIT) and a test using the task materials. In this latter test the children were shown picture cards of the twins wearing some of the clothing items for 15 seconds. They then had to place cut-outs of the clothing items correctly in one of three boxes depending on who had been wearing them: "Anna", "Sally" or "Both". A working memory capacity score (WM) was calculated based on the number of items the child could consistently place in the correct box.

Results

Cluster analysis identified five main strategic patterns of response by the children to the MDL task. A subsequent discriminant function analysis established a clear developmental pattern. Table 3 reports each Strategy Cluster's score on the first function from this analysis (F1, which accounted for over 61% of the variance), and the predominant age group of the children exhibiting that strategic pattern. There is not space in this paper to explore the details of these different strategic patterns, but an indication of the main characteristics of each pattern is given for the purposes of identification (for more detail of these strategies see Whitebread, 1996).

Significantly for the issues under discussion in the present paper, the more sophisticated strategic patterns on the MDL task differ from that on the Reclassification task in that they appear to involve more working memory capacity rather than less. With each increase in sophistication, the child incorporates more information from across more trials in order to identify more quickly the one item of clothing which always stays with "Anna". The other relevant factor here is that Strategy Clusters 1 and 6 involved the production of a high number of hypotheses on each trial, while children using Strategy Clusters 4 & 2 produced a low number of hypotheses on each trial, often only one. These two response styles make very different demands on working memory capacity. The most sophisticated Focusing strategy of Strategy Cluster 3 involved a more accurate and intermediate number of hypotheses being produced on each trial.

Overall, the various metacognitive abilities assessed emerged as the strongest predictors of performance on the task, but with different metacognitive and working memory capacity elements being associated with performance for each of the five Strategy Clusters, as also reported in Table 3. Thus, for the developmentally simplest Strategy Cluster 4 performance was most closely related to strategic control and overall metacognitive abilities. For other 6 yr. olds exhibiting Strategy Cluster 1, however, which involved a high number of hypotheses, working memory for the task materials and metacognitive knowledge were most significant. Amongst 8 yr. olds exhibiting the predominant Strategy Cluster 2 scores on the Figural Intersections Test (FIT) of working memory capacity and metacomprehension were most closely associated with performance. By contrast, the performance of 10 yr. olds using the Strategy Cluster 6 approach was unrelated to any working memory or metacognitive measures. For those 8 and 10 yr. old children using the developmentally most sophisticated approach of Strategy Cluster 3, however, working memory for the task materials and strategic control were both significantly related to performance.

Table 3

Discriminant function analysis first function scores (DSFN F1), predominant age groups and associated cognitive processes for 5 main Strategy Clusters

Cluster	DSFN F1 score	Predominant age group	Associated cognitive process
4 (High/Random Shift of Hypotheses)	70.24	6 year olds	Strategic control Overall metacognitive abilities score
1 (Attribute/Dimension Perseveration)	72.96	6 year olds	Working memory capacity related to task materials Metacognitive awareness
2 (Negative Information Difficulties)	76.45	8 year olds	Figural Intersections Test Metacomprehension
6 (High Hypotheses per Trial)	78.17	10 year olds	______________
3 (Focusing)	80.33	8 & 10 year olds	Working memory capacity related to task materials Strategic control

Once again, therefore, developmentally changing interactions emerged between working memory capacity, metacognitive abilities, strategy construction and choice, and performance. The developing pattern of interactions was more complicated, probably as a result of the more complex nature of the task and the wider age group. As with the Reclassification task, however, clearly different patterns of interaction emerged depending upon the level of metacognitive abilities. Table 4 reports correlations between the various cognitive processes and performance on the MDL task for two "metacognition subsets" comprising those children whose overall metacognitive abilities scores were above (the "strong" metacognitive abilities group) and below (the "weak" metacognitive abilities group) the population mean.

For the children in the weak metacognitive abilities group their level of performance was, once again, more dependent upon working memory capacity. The results in Table 4 reveal three correlations significant at the .05 level with WM (working memory capacity using task materials) and FIT (the Figural Intersections Test). Where metacognitive abilities were relatively strong, on the other hand, no such relationship with working memory capacity existed on either measure. This would appear to be evidence of children with well developed metacognitive abilities, including good self-monitoring and metacomprehension, more efficiently choosing strategies which best match their working memory capacity in relation to the task.

Table 4

Correlations of scores on cognitive processes and MDL task performance for metacognition subsets

	Performance indicators					
	Total			Learning		
Cognitive processes	TLE	VCH	H123	TLE	VCH	H123
Metacognitive awareness Q1						
Weak[1]	.25	.27	.04	-.03	.08	-.31
Strong[2]	.30	.33*	.17	.24	.01	-.01
Metacognitive awareness Q2						
Weak	.25	.15	.32	.18	-.20	.08
Strong	-.04	.09	-.00	.21	-.10	-.19
Metacognitive awareness Q3						
Weak	.06	.12	.02	.11	-.11	-.19
Strong	-.08	-.03	-.01	.00	-.13	-.04
Metacomprehension						
Weak	.09	.02	.22	.03	.04	.24
Strong	.32	.20	.22	.50**	-.13	.04
Strategic control						
Weak	.22	.21	.12	-.17	.17	.22
Strong	-.12	.03	.11	-.27	-.08	.18
Overall metacognitive abilities score						
Weak	.47**	.44**	.36*	.08	-.02	-.07
Strong	.10*	.27	.24	.18	-.21	.05
Working memory capacity related to task materials						
Weak	.34*	.31	.38*	-.07	.13	-.03
Strong	.25	.18	.19	.09	-.19	.00
Figural Intersections Test						
Weak	.32	.32	.33*	-.27	.04	.06
Strong	.11	.02	.14	-.12	.13	-.00

Note. *=sig at .05; **=sig at .01; TLE=Trial of Last Error; VCH=Verbalisation of Correct Hypothesis; H123=Hypotheses on Trials 1, 2 & 3; [1] the term "weak" denotes weak metacognitive abilities: overall score below population mean; [2] the term "strong" denotes strong metacognitive abilities: overall score above population mean.

The other very striking result arising from this analysis, which tends to support this position, was the dear association between metacomprehension and performance for the strong metacognitive abilities group, particularly in relation to learning over the course of carrying out the 6 problems. The measure of metacomprehension for this group correlated at the .01 level of significance with TLE (Trial of Last Error, a measure of the number of trials needed to solve problems). This would support the view that there are important interactions between different metacognitive processes. Being aware of their own level of understanding appears to have been a necessary but not sufficient requirement for the children to develop more effective strategies to tackle new problems. For the cognitive outcomes of metacomprehension to be translated into improved performance on the MDL task depended crucially on overall metacognitive ability, including metacognitive awareness (leading to metacognitive knowledge of the task) and strategic control. Where these other aspects of metacognitive ability were weak, good metacomprehension had no effect.

The overriding significance of metacognitive abilities is further supported by the result for the overall metacognitive abilities score for the weak metacognitive abilities group (two performance indicators significant at the .01 level, and one at the .05 level).

Differential patterns also emerged, once again, within different age groups. Table 5 reports correlations between the various cognitive process measures and performance on the MDL task for children in the three age groups (results for Learning are not reported here as no very clear patterns emerged).

Table 5

Correlations of scores on cognitive processes and MDL task performance for the three age groups

	Performance Indicators								
	6 years old			8 years old			10 years old		
Cognitive processes	TLE	VCH	H123	TLE	VCH	H123	TLE	VCH	H123
Metacognitive awareness Q1	.43*	.43*	.35	-.01	.09	.20	.75**	.75**	.27
Metacognitive awareness Q2	.40	.24	.20	.08	.11	-.14	.22	.30	.35
Metacognitive awareness Q3	.05	.15	.09	-.04	.06	.04	.37	.23	.08
Metacomprehension	.28	.34	.10	.38	.28	.45*	.61**	.49*	.44*
Strategic control	.26	.31	.34	.15	.16	.29	.39	.47*	.26
Overall metacognitive abilities score	.63**	.68**	.50*	.20	.24	.33	.81**	.79**	.48*
Working memory capacity related to task materials	.36	.32	.32	-.00	-.08	-.36	.52**	.52**	.62**
Figural Intersections Test	.26	.25	.15	.22	.19	.05	.45*	.38	.31

Note. *=sig at .05; **=sig at .01 level; TLE=Trial of Last Error; VCH=Verbalisation of Correct Hypothesis; H123=Hypotheses on Trials 1, 2 & 3.

Thus, on the Reclassification task, whereas metacognitive awareness and working memory capacity were both strongly related to task performance for 6 year olds there were no such relationships for the 5 year olds. On the MDL task, a similar pattern emerged for working memory capacity with both measures (WM & FIT) being significantly related to performance for the 10 year olds, but not for the younger age groups. At this point it is interesting to note also that the WM measure of capacity in relation to the actual task materials was more closely related than the more general FIT capacity measure [which would be predictable from Case's (1985) work]. For overall metacognitive abilities, however, there was evidence of a U-shaped pattern of development, with a significant relationship to performance for the 6 and 10 year olds, but no such relationship for the 8 year olds. It is difficult to make direct comparisons between the two studies, however, because of the different age ranges and the different relationship between strategies and working memory capacity alluded to earlier. The consistent finding which emerges, however, is that the relationships between metacognition, working memory capacity, strategy choice and performance change and develop.

Interestingly, the aspect of metacognitive ability which was most critical for both the 6 and 10 year olds appeared to be that aspect of metacognitive awareness and knowledge measured by their ability to answer Question 1, which asked them which of the three types of MDL problems (standard, irrelevant & negative information) they had found easiest and which most difficult. Their score depended upon the accuracy of their judgement in relation to their own relative success on the three types of problems. The other aspect which was critical for the 10 year olds was metacomprehension.

Taken together, all these results suggest a model which incorporates the different relationships between strategies and working memory capacity demands, and between children's developing ability to construct and choose strategies which are more accurately attuned to the demands of particular tasks and their own current working memory capacity in relation to them. A range of metacognitive abilities involving monitoring of performance and strategic control are clearly central to these dynamic relationships.

Theoretical and educational implications

The two studies reported here have significant implications for psychological theory and research, and for educational practice.

The results of both studies support the view that children's developing cognitive abilities need to be understood in terms of interactions between different elements of their cognitive and metacognitive processing. Such an analysis will help us to understand typical patterns of development and to determine which aspects of cognitive processing are likely to be most critical at different points in development.

It is, furthermore, particularly important to look at the ways in which these various cognitive factors interact with one another. A growing amount of research in recent years has begun to address this issue. For example, Bjorklund's (1990) useful collection of recent work on children's strategies contains a number of studies each of which address different aspects of cognitive processing which interact with children's use of strategies. Schneider and Weinert (1990) have edited a collection of studies devoted to the analysis of interactions between aptitudes, knowledge components and cognitive strategies. In a review of work related to memory development, they have themselves (Schneider & Weinert, 1989) produced an integrative model of the contribution of basic capacities, strategies, metamemory and content knowledge to memory development, each of which makes a contribution at different stages. Clearly, this work needs to be continued and developed. The present study contributes to this kind of analysis in relation to the development of problem-solving abilities.

Various particular interactions between cognitive factors have been revealed by the present studies, particularly those between working memory capacity, metacognitive abilities, strategy construction and choice, and performance. Schneider and Weinert (1989) have reviewed evidence suggesting that metacognitive abilities might become more closely related to performance as children grow older. While this is generally supported by the present studies, however, the relationship had a more U-shaped pattern in the case of the MDL task. This is a finding which it would be very interesting to explore further. One clear possibility is that different patterns will emerge in relation to different kinds of problems. Thus, for example, the Reclassification task lends itself to an improved strategy (the "descending" strategy) which greatly reduces load on working memory. The more sophisticated strategies on the MDL task, however, tended to increase working memory load. The patterns of interactions between working memory capacity, metacognition and strategy choice are clearly dependent on such task characteristics.

Within the educational sphere, the present studies emphasise the significance of fostering certain kinds of metacognitive abilities. The work in Britain of Nisbet and Shucksmith (1986) and in America of Borkowski, Brown and their co-workers [see, for example, Pressley, Borkowski, & O'Sullivan (1985) and Campione (1987)] has demonstrated that metacognitive abilities can be developed through teaching, and has begun to indicate the kind of pedagogical principles upon which such teaching must be based. Nisbet and Shucksmith (1986), in particular, argue that just making children aware of what they do not know or understand will not necessarily foster the ability or the desire to learn more effectively. Children also need to be shown how to learn. This is well supported by the evidence from the present study of children who scored well on metacomprehension, but nevertheless performed relatively poorly on the MDL task. Metacomprehension was only well related to improved performance where other metacognitive abilities were in place.

While there is a resurgence of interest in "active learning" within education at the moment, its impact is relatively limited, and many teachers could be much better informed about the significance of metacognitive processes for learning. English (1992), for example, has shown that within the mathematics curriculum children as young as 4 yrs. old can usefully be helped to engage in self-monitoring, and in the more explicit use of strategies. The results of the studies reported here, showing the complex and interactive nature of a range of metacognitive abilities, strategy use and performance, would tend to support the view expressed some time ago by Flavell (1978) that early strategy use, combined with declarative knowledge about strategies, is likely to increase metacognitive awareness and control, which will, in turn, lead to the construction and use of more extensive and more sophisticated cognitive strategies.

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Cet article rapporte les résultats de deux recherches destinées à explorer les interactions entre capacités métacognitives de l'enfant, capacité de la mémoire de travail, développement et sélection de stratégies, et performances à des tâches de résolution de problème. Dans la première étude, un échantillon de 20 enfants âgés de 5 ou 6 ans, était soumis à une tâche de reclassification. Dans la deuxième recherche, un échantillon de 72 enfants âgés de 6, 8 ou 10 ans était confronté à une tâche d'apprentissage de discrimination multidimensionnelle. Les résultats montrent que les performances aux deux tâches, dépendent des changements développementaux dans l'interaction entre les différents aspects du fonctionnement cognitif cités plus haut et mesurés dans cette recherche. En particulier, les relations entre mémoire de travail et performance dépendent des compétences métacognitives. Les résultats montrent aussi que la conscience métacognitive n'affecte pas directement les performances, mais que la relation entre les deux dépend du développement du contrôle stratégiques. Les explications des ces résultats pour l'interprétation des patrons de développement courants ou des évolutions en forme de U sont discutées. Dans le champ de l'éducation, l'étude contribue à mettre en valeur l'intérêt et la possibiblité d'encourager le développement de certains types de capacités métacognitives.

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David Whitebread. Homerton College, Hills Rd., Cambridge CB2 2PH, England, UK, Tel: +1-223-507291, Fax: +1-223-507120, E-mail: dgw1004@hermes.cam. ac.uk.

Current theme of research:

Development of children's metacognitive and strategic processing in problem solving and educational settings (particularly in relation to mathematics, IT, independent learning and road safety).

Most relevant publications in the field of Psychology of Education:

Whitebread, D. (1995). Emergent mathematics *or* how to help young children become confident mathematicians. In J. Anghileri (Ed.), *Children's thinking in primary mathematics: Perspectives on children's learning*. London: Cassell.

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