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Students' Ability to Solve Process-diagram Problems in Secondary Biology Education

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Process diagrams are important tools in biology for explaining processes such as protein synthesis, compound cycles and the like. The aim of the present study was to measure the ability to solve process-diagram problems in biology and its relationship with prior knowledge, spatial ability and working memory. For this purpose, we developed a test that represents process diagrams and adjacent tasks used in secondary education biology. Results show that the ability to solve process-diagram problems is correlated to prior knowledge, spatial abilities and visuospatial working memory capacity. A difference in impact of spatial skills was demonstrated for the level of cognitive demand when solving process-diagram problems.

Keywords: *Process diagram; Problem-solving; Secondary biology; Spatial ability*

Introduction

Diagrams are important tools in science education. They allow us to communicate abstract information. Diagrams explain natural phenomena that cannot be directly observed as they are, for example, too small, too large, too slow or too fast. Process diagrams form a distinct class of diagrams: they convey functional information about a dynamic process by the spatial configuration of components and arrows. In biology, process diagrams explain processes such as protein synthesis, immunology, photosynthesis, cellular respiration, compound cycles, and the like (*eg* Reece et al. 2010). In biology education, students are faced with process-diagram problems that require them to select and extract, to interpret and to infer the presented information.

Although diagrams aim to facilitate learning (Larkin and Simon 1987; Winn 1993), students have difficulties with diagram interpretation (*eg* Schönborn, Anderson, and Grayson 2002). Previous studies have found that prior knowledge (*eg* Cook 2006),

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working memory and spatial skills (*eg* Hegarty and Sims 1994) and task demand (*eg* Guthrie, Shelley, and Kimmerly 1993) contribute to the interpretation process of scientific representations. The present study's focus is on providing more insight into students' ability to solve process-diagram problems in biology in secondary education.

Theoretical Framework

Two frameworks are relevant for problem-solving with diagrams: the working memory model of text and picture comprehension of Schnotz and Bannert (2003) and the cognitive load theory (Sweller 1994).

Working Memory

In Schnotz and Bannert's model (2003), text and diagrams are processed through verbal and visual systems in working memory to construct an integrated mental model. Prior knowledge has a selective and organisational function. Students with little prior knowledge have more difficulties in creating effective mental models (Mayer and Moreno 2003). The construction of a mental model draws on cognitive resources of the visuospatial sketchpad (Sims and Hegarty 1997). Students with high spatial ability can devote more resources to building referential connections between the visual and verbal mental model than low spatial ability learners can (Mayer and Sims 1994).

Cognitive Load Theory

The cognitive Load Theory (Sweller 1994) assumes a limited working memory storage capacity and unlimited long-term memory storage capacity. Intrinsic cognitive load is high when materials include many interacting elements. Working memory limits then make it difficult to assimilate the presented information. In such a case, long-term memory expands the processing abilities of working memory by the storage of information into schemas, *ie* cognitive constructs that incorporate multiple elements of information into a single element. When knowledge schemas are available they can be brought to working memory as chunks and thereby reduce cognitive load.

Problem Solving

Kindfield (1993) concluded that the use of representations in reasoning and problem-solving co-evolves with domain expertise. Experts possess schemas that contain declarative and procedural knowledge which is used for *problem-solving* processes (Chi, Feltovich, and Glaser 1981). Larkin et al. (1980) found that the availability of schematas facilitated efficient search in diagrams. It also guides the interpretation of a problem and the formulation of a solution (Chi, Feltovich, and Glaser 1981).

Prior Knowledge

Cook (2006) showed that prior knowledge is one of the strongest determining factors for success in learning from representations. Domain knowledge affects information selection, encoding, interpretation and inferencing from diagrams.

Prior knowledge is important for *selecting* task-relevant information in a diagram. Novices focus on surface features of a domain-specific diagram, whereas experts attend to more relevant content (Canham and Hegarty 2010; Chi, Feltovich, and Glaser 1981; Cook, Carter, and Wiebe 2008). For instance, Cook and colleagues (2008) compared the interpretation process of students with low and with high prior knowledge of cell transport diagrams, *ie* diffusion and osmosis. Low prior knowledge students focused less on relevant features, *eg* a concentration gradient or an active transport zone, when these features were not specifically emphasised in the diagram. When task-relevant information is found it must be further *encoded* to construct an integrated mental model (Schnotz and Bannert 2003).

Prior knowledge also affects *interpretation* and *inference* processes *after* the presented information is encoded. Kragten, Admiraal, and Rijlaarsdam (2012) found that absence of domain knowledge impaired the interpretation of process diagrams when cognitive task demand was high, but not when cognitive task demand was low.

Spatial Ability and Working Memory

Spatial ability and working memory relate to students' problem-solving ability with regard to scientific diagrams (*eg* Bodner and McMillen 1986), especially when it requires spatial transformation processes (Hegarty and Sims 1994), visualisation (Kozhevnikov, Hegarty, and Mayer 2002) and mental model construction (e.g., Mayer and Sims 1994).

Various studies report that spatial ability and chemistry problem-solving are related (see Wu and Shah 2004 for an extensive review about this issue) both in spatial and in non-spatial higher-order cognitive tasks (*eg* Bodner and McMillen 1986; Pribyl and Bodner 1987). Wu and Shah (2004) conclude that understanding both types of tasks, spatial and non-spatial, required a similar ability to disembed and restructure problems.

Hegarty and Sims (1994) found that high spatial ability and performance on tasks involving the mental animation of a mechanical system are related. They suggest that poor performing participants with low spatial ability might process spatial transformation inaccurately or have a visuospatial sketchpad with a smaller capacity. Kozhevnikov, Hegarty, and Mayer (2002) presented graphs of motion to high and low spatial ability participants and asked them to visualise and interpret the motion of an object. High spatial ability participants interpreted the graph as an abstract schematic representation and generated a correct description of the object's motion; low spatial ability participants tended to interpret the graph literally as a pictorial illustration of a situation. In addition, Kozhevnikov, Motes, and Hegarty (2007) found that low spatial ability participants had problems solving kinematics problems when they had to combine two motion vectors or switch their frames of reference.

Previous research has mostly focused on physics and chemistry and used a small number of representations and tasks. The present study measures the ability to solve process-diagram problems in biology and the relationship with prior knowledge, spatial ability and working memory. For this purpose, a test involving process-diagram problems was designed. In the method section, we formulate several hypotheses about the relation between performance on the process-diagram test and prior knowledge, spatial ability and working memory.

Method

Participants

The participants were 42 secondary school pre-university students from a high school in the Netherlands (mean age 18 years, 22 females). The students participated voluntarily. For the last three years of their study in secondary education they chose biology as a major topic within their exam programme, for which they received 480 hours of education.

Data Collection

Data collection was spread over two days within a two-week period. The tests were planned just before the students' final national exams and were administered during school time in a classroom at their school.

Process-diagram Test

To provide evidence of whether the process-diagram test contains a representative sample of process diagrams and tasks, we will describe the construction process and the included process diagrams and justify the tasks included. In the results section, we will report on homogeneity and descriptive statistics.

Construction. The process-diagram test was designed in two stages. First, the first and second authors (respectively a part-time high school biology teacher with 10 years' experience and an expert in the construction of national exams) designed an initial version of the process-diagram test and the scoring model. Two external national exam experts and another high school biology teacher evaluated this first version and confirmed face validity. The external experts' suggestions for improvement led us to revise the final version.

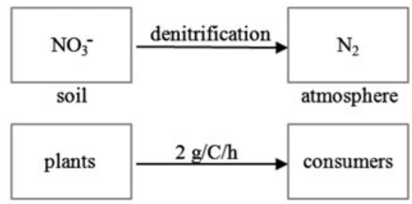
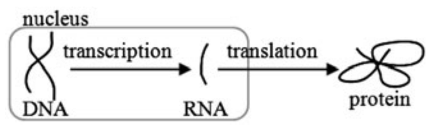
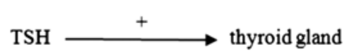
Process diagrams. We included a total of 28 diagrams in the test (Table 1), selected from previous national biology exams, biology textbooks (*eg* Reece et al. 2010) and the Internet. We redesigned most of the diagrams so they could be understood without any additional instructional, explanatory and/or contextual text.

The process-diagram test aims to contain a good reflection of process diagrams used in secondary education biology; therefore we selected four biological topics: ecology, protein synthesis, dissimilation and hormones. The diagrams we selected include a variety of components (range = 1–30), arrows (range = 2–29) and conventions (from abstract text boxes to less abstract iconic pictures). Diagrams used for instruction were not included in the process-diagram test as we felt it was important that students had not previously seen any of the diagrams included in the process-diagram test.

Tasks. The process-diagram test consists of 97 tasks. Students' ability to solve process-diagram problems was measured by their performance on these tasks. All tasks were scored as correct or incorrect.

Each topic of the process-diagram test contains tasks with low cognitive demand and tasks with high cognitive demand (Table 2 presents some examples). We categorised the

Table 1. Diagrams included in the process-diagram test

Topic	Diagrams	Tasks LCTD	HCTD	Examples
Ecology	Carbon cycle on earth	6	2	
	Food web in a fresh lake	2	0	
	Carbon cycle in an American lake[a]	3	3	
	Flow of energy tropical rainforest	–	2	
	Nitrogen cycle on earth	7	–	
	Phosphorous cycle in a Dutch fresh lake	4	–	
	Nutrient cycle in an ecosystem	6	–	
	Balancing the nitrogen cycle in Dutch agriculture	–	3	
	A global climate model[b]	1	2	
	Nitrogen cycle in traditional Chinese agriculture	3	–	
	Total	*32*	*12*	
Protein synthesis	Infection with a retrovirus	8	1	
	The lytic and lysogenic cycle of a bacteriophage	–	1	
	Translation at a ribosome	5	1	
	Tryptophan synthesis and feedback	1	4	
	Total	*14*	*7*	
Dissimilation	Decarboxylation and citric acid cycle	–	4	
	Anaerobic dissimilation of glucose	1	–	
	Dissimilation and the formation of ATP	2	2	
	Oxidative phosphorylation	1	1	
	Dissimilation of glucose by two bacteria[a]	2	2	
	Glycolysis	3	–	
	Total	*9*	*9*	
Hormones	Hormonal regulation of sperm production	4	–	
	Negative feedback after injection with hormones	–	1	
	Feedback and hormonal effects	–	1	

(*Continued*)

Table 1. (*Continued*)

Topic	Diagrams	Tasks LCTD	HCTD	Examples
	A theoretical model of hormonal regulation	2	–	
	Pituitary gland, ovaries and uterus[a]	1	–	
	Hormonal regulation of growth in a human	1	1	
	Types of feedback loops[a]	1	–	
	Indigestion hormones of the stomach	–	2	
	Total	*9*	*5*	

Note. LCTD = low cognitive task demand; HCTD = high cognitive task demand
[a]A depiction with multiple diagrams that a student, for instance, had to compare.
[b]The arrows of this climate model represent a feedback mechanism, i.e., see hormones.

tasks based on Guthrie, Shelley, and Kimmerly (1993), Crowe, Dirks, and Wenderoth (2008), Kragten, Admiraal, and Rijlaarsdam (2012) and the cognitive load theory (Sweller 1994).

Tasks with low cognitive demand require only a few elements to be explored and/or element interactivity is low. Once the relevant information is selected and encoded, formulating a correct answer requires little cognitive processing: the information can be easily read from the diagram. These tasks require, for instance, summarising the elements found, describing a part of the process step-by-step and/or some simple calculations such as adding or subtracting amounts. For instance, to answer the first low cognitive task from Table 3, a student can easily calculate the increase or decrease per compartment (adding the incoming arrows and subtracting the outgoing arrows). The student calculates each compartment independently, so element interactivity is low.

A task with high cognitive demand is usually more global (Guthrie, Shelley, and Kimmerly 1993); a large part or the entire diagram needs to be explored and the components interact. Once the selected information is found, a mental model must be built in working memory (Buckley 2000) and integrated (evaluated, inferred, compared, judged) with prior knowledge.

Table 2. Examples of tasks with a high and low cognitive demand from the process-diagram test

Low cognitive task demand

1. There are compartments in which the amount of carbon decreases. Give the name and the amount of decrease of these compartments. (Carbon cycle on earth)
2. Describe each step (1–8) of the infection with a retrovirus. (Infection with a retrovirus)

High cognitive task demand

1. Paul states: 'If the combustion of fossil fuel remains 5 Gigatons a year then it will increase by 50 Gigatons in 10 years'. Reason why this statement is wrong. (Carbon cycle on earth)
2. Explain how the loss of half products, *eg* α-ketoglutarate, during the citric acid cycle can be compensated. (Decarboxylation and citric acid cycle)

Note. 'Between parenthesis' is the name of the diagram in Table 1 that was presented with the task.

We expected the scores on these two task types to differ significantly, as this indicates the validity of these concepts in the process-diagram test. Furthermore, we expected scores on tasks with low cognitive demand and high cognitive demand would be correlated because both task types were predicted to rely on prior knowledge and selecting and encoding the information in the presented diagram.

Prior Knowledge, Spatial Ability and Working Memory Tests

The tests of prior knowledge, spatial ability and working memory, and their hypothesised relationship with low or high cognitive demand tasks in the process-diagram test, are presented in Table 4.

Prior knowledge. Students' prior knowledge about the topics in the process-diagram test was measured by a test including 56 open and closed questions. The prior knowledge test consists of questions asking for the recall of basic concepts, *eg* 'What is the definition of an ecosystem?' and tasks asking for the understanding of processes, *eg* 'What is the role of a producer in an ecosystem?' We hypothesise that prior knowledge relates positively to both low and high cognitive task demand. Achievement on a task with low cognitive demand relies on searching and encoding information, facilitated by domain-specific knowledge (Winn 1993). The presence of knowledge schemas facilitates achievement in a task with high cognitive demand because such schemas keep cognitive load low (Mayer and Moreno 2003).

Spatial ability. For the present study, a number of spatial ability tests were selected from the Ekstroms' kit of factor-referenced cognitive tests (Ekstrom et al. 1976). These tests were used in previous research on learning science and interpreting scientific diagrams (*eg* Hegarty and Sims 1994; Kozhevnikov, Hegarty, and Mayer 2002; Kozhevnikov, Motes, and Hegarty 2007) and dual-coding working memory models (e.g., Mayer and Sims 1994). For reasons of parsimony we will not describe these tests in full here, because they have been discussed extensively in previous literature.

For spatial orientation and visualisation, we included the Card Rotation Test, Cube Comparisons Test, Form Board Test, Paper Folding Test and Surface Development Test. These tests require the manipulation of a figure's spatial orientation; for visualisation, the figure must first be restructured.

The interpretation of process diagrams requires a specific set of procedural knowledge. For instance, although the main theme of an ecological diagram might be carbon flux (*ie* movement of carbon per unit of time), mentally visualising the flow of carbon would not be a very effective strategy. It is more likely that a participant would encode the diagram into a more static mental model and a propositional causal model. Then the participant may explore solutions to the problem (Schnotz and Bannert 2003) in a piecemeal manner (Hegarty 1992) by applying rules and conventions.

We therefore hypothesised that the tests on visualisation and spatial orientation factors were uncorrelated to both low and high cognitive demand tasks in the process-diagram test. Indeed, process-diagram tasks do not require rotation or actual visualisation of the movement of components: Most studies that found correlations between visualisation and/or spatial operation factors and interpretation of scientific diagrams focused on tasks that require mental operations (*eg* Hegarty and Sims 1994; Kozhevnikov, Hegarty, and Mayer 2002; Mayer and Sims 1994). The Choose a Path Test, a marker test for the spatial scanning aptitude factor (Ekstrom et al. 1976), was also administered. In this test, each item consists of a diagram with a network of lines; participants must find a line that connects two components among a complex field of dead ends. Scores on the Choose a Path Test were expected to be influenced by students' ability to configure and discriminate the presented elements, a crucial step when people search for information in a diagram (Winn 1993). We hypothesised that achievement on tasks from the process-diagram test with low cognitive demand will positively correlate with scores on the Choose a Path Test because these tasks focused primarily on selecting the correct information. Scores on tasks with high cognitive demand will not correlate to the Choose a Path Test scores because these tasks require skills such as making inferences, in addition to selecting and encoding information.

Working memory. Miyake et al. (2001) concluded that simple storage-oriented tasks in the visuospatial domain are good predictors for the amount of storage in the visuospatial sketchpad and the closely connected central executive, *ie* the regulating and controlling system of working memory (Baddeley 1986).

The Shape Memory Test (Ekstrom et al. 1976) measures the ability to remember a group of shapes and their positions in relation to each other. The shapes are abstract forms that one cannot easily encode in any modality other than visual. Students with smaller visual working memory capacity could experience cognitive overload when the cognitive task demand is high. For tasks with high cognitive demand, students need to build and explore a mental model that draws on the capacity of visuospatial memory (Sims and Hegarty 1997). For this, we expect that visual working memory correlates to high cognitive task demand. For low cognitive tasks, there is no need to build complex mental models because the task does not demand this strategy, *ie* students approach a diagram in a goal-based manner (Winn 1993).

Data Analysis

First, we calculated descriptive statistics for the process-diagram test, the prior knowledge test and the spatial ability and working memory tests. The process-diagram test and the prior knowledge test were also tested for internal reliability, indicated by KR-20. We then used correlations to show the relationships between the process-diagram test, on the one hand, and prior knowledge, spatial ability and working memory, on the other.

Results

Students' Ability to Solve Process-diagram Problems

Table 3 presents the descriptive statistics for the process-diagram test, the prior knowledge test, the spatial ability tests and the working memory test. The average score

Table 3. Descriptive statistics for the process-diagram test, spatial ability tests and working memory test and prior knowledge test

Variable	Test	Scoring items	Min	Max	*M*	*SD*
Low cognitive task demand[1]	Process-diagram test	64	19	56	41.14	8.54
High cognitive task demand[2]		33	3	26	14.17	6.03
Spatial ability:						
Spatial orientation	Card Rotation Test	80	32	80	63.00	12.29
	Cube Comparisons Test	21	1	19	11.33	3.58
Spatial scanning	Choose a Path Test	16	1	16	9.90	4.65
Vizualisation	Form Board Test	24	3	20	11.52	4.39
	Paper Folding Test	10	−1	10	5.81	2.80
	Surface Development Test	30	−5	30	22.38	8.49
Working memory	Shape Memory Test	16	3	15	9.79	3.67
Prior knowledge	Prior knowledge test[3]	56	26	49	38.81	6.28

Note. Min = minimum score of a student; Max = maximum score of a student. The prescribed scoring procedure from Ekstrom et al. (1976) was adopted.
[1] KR-20 = .85.
[2] KR-20 = .82.
[3] KR-20 = .78.

on 64 tasks (M = 41.14, SD = 8.54) of the process-diagram test with low cognitive demand was 64% correct (range = 30–88%). The average score on 33 tasks (*M* = 14.17, *SD* = 6.03) of the process-diagram test with high cognitive demand was 43% correct (range = 9–79%).

For the process-diagram test, internal reliability indicated by KR-20 was .85 for tasks with a low cognitive demand and .82 for tasks with a high cognitive demand. Figure 1 presents the boxplot and a scatterplot for students' scores as percentages of correct

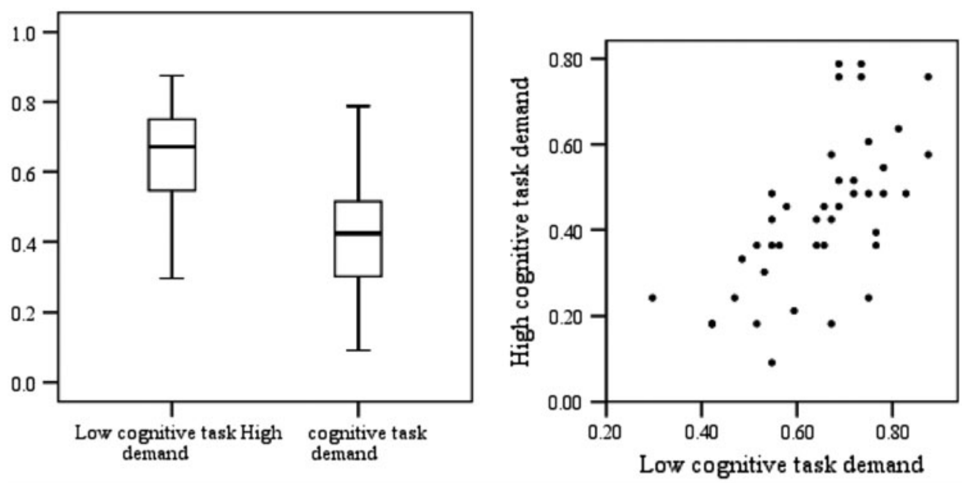


Figure 1. Boxplot and scatterplot for students' scores on tasks of the process-diagram test with low and high cognitive demand. The scores are presented as percentages of correct answers

Table 4. Predictions and correlations between the process-diagram test and spatial ability, working memory and prior knowledge

		LCTD		HCTD	
Variable	Test	Prediction	*r*	Prediction	*r*
Prior knowledge	Prior knowledge test	+	**.46****	+	**.38***
Spatial ability:					
Spatial scanning	Choose a Path Test	+	**.41****	–	**.18**
Spatial orientation	Card Rotation Test	–	**.19**	–	**−.04**
	Cube Comparisons Test	–	**.07**	–	**.12**
Visualisation	Form Board Test	–	**.14**	–	**.14**
	Paper Folding Test	–	**.12**	–	**−.05**
	Surface Development Test	–	.53**	–	.43**
Working memory	Shape Memory Test	–	**.20**	+	**.41****

Note. Predicted correlations are presented by a plus (+; correlated) or minus (–; uncorrelated) sign. Correlations found (*ie* correlated and uncorrelated) that were hypothesised are printed in **bold**. LCTD = Low cognitive task demand; HCTD = High cognitive task demand.
*$p < .05$ (2-tailed).
**$p < .01$ level (2-tailed).

answers on tasks of the process-diagram test with low and high cognitive demand. A paired-samples *t*-test showed that students successfully completed significantly more tasks involving low cognitive demand (M = .64, SD = .13) than tasks with high cognitive demand (M = .43, SD = .18; $t(41)$ = 10.00, $p < .001$, $d = 1.34$). Tasks in the process-diagram test with low cognitive demand and tasks with a high cognitive demand correlated significantly, r = .66, $p < .01$.

The scores on the prior knowledge test (M = 38.81, SD = 6.28) were relatively high, with an average score of 69% correct answers, ranging from 46% to 88% correct. KR-20 for the prior knowledge test was .78 after removal of two items.

The Relationship between the scores on the Process-diagram Test and the Explanatory Tests Included

As hypothesised, scores on tasks of the process-diagram test with low cognitive demand correlate significantly with scores on the prior knowledge test (r = .46) and the Choose a Path Test (r = .43); the significant correlation with the Surface Development Test (r = .53) had not been hypothesised[1] (Table 4). We found no significant correlations, as hypothesised, between low cognitive task scores and the Card Rotation Test, the Cube Comparison Test, the Form Board Test, the Paper Folding Test and the Shape Memory Test.

High cognitive task scores from the process-diagram test correlated, as hypothesised, significantly to the prior knowledge test (r = .38) and the Shape Memory Test (r = .41); the significant correlation with the Surface Development Test (r = .43) was not hypothesised. We found no significant correlations, as hypothesised, between high cognitive task scores and the Choose a Path Test, the Card Rotation Test, the Cube Comparison Test, the Form Board Test and the Paper Folding Test.

Discussion

The present study measured the ability to solve process-diagram problems in biology and its relationship with prior knowledge, spatial ability and working memory. The process-diagram test developed in this study contains a valid representation of process diagrams and adjacent tasks used in secondary education biology. The test consists of 97 tasks (64 low and 33 high cognitive demand) and 28 diagrams. The mean scores on tasks with low and high cognitive demand differed significantly; the internal homogeneity of both subtests was high. Therefore we conclude that task difficulty was operationalised reliably and validly. Both subtests correlated. It seems that similar skills and knowledge accommodate achievement on both task types.

As hypothesised, scores on the prior knowledge test correlated positively with tasks with low and high cognitive demand. We expected prior knowledge would correlate to low cognitive task demand because it facilitates search (Winn 1993) and with high cognitive demand because knowledge schemata keep cognitive load low. The correlation between the prior knowledge test and tasks with high cognitive demand in the process-diagram test was moderate (though significant).

Scores on the Choose a Path Test also positively correlated, as hypothesised, with low cognitive demand tasks. We assume the Choose a Path Test to be a measure for the ability to search for information in a complex spatial diagram.

We hypothesised that tests from the visualisation and spatial orientation factors would be uncorrelated to scores on tasks from the process-diagram test with low and high cognitive demand. The latter was confirmed except in the case of scores on the Surface Development Test, which correlated with scores on both low and high cognitive demand tasks. The strong correlation between the Surface Development Test and the Choose a Path Test might explain this unexpected finding. Presumably both tests tap, to some extent, the same ability, *ie* configuring elements in a complex spatial field.

Performance on tasks of the process-diagram test with high cognitive demand was expected to correlate to scores on the Visual Memory Test. The Visual Memory Test was expected to be a measure of the capacity of the visuospatial sketchpad available for constructing a runnable mental model. A moderate correlation was found between the Visual Memory Test scores and task scores from the process-diagram test with high cognitive demand.

We conclude that the ability to solve process-diagram problems involves the presence of prior knowledge, spatial abilities and visuospatial working memory capacity. This study thereby adds to a large body of previous research on the role of these factors in learning from external representations. The correlations we found are, however, not fully congruent with previous studies (*eg* Hegarty and Sims 1994; Kozhevnikov, Hegarty, and Mayer 2002; Mayer and Sims 1994) and show that solving process-diagram problems with low and high cognitive demand both require different spatial skills.

A limitation of the present study is the specific focus on biological process diagrams. We chose these types of diagrams because of their significance in teaching and learning biology, but would hesitate to generalise the findings to other types of diagrams (*eg* tree or anatomical diagrams) or other scientific domains. Furthermore, we only found moderate correlations, suggesting that other factors (*eg* strategy use, understanding conventions, etc.) might also be important in process-diagram problem-solving.

All in all, we think this study might help the biology education community. The study stresses that prior knowledge must be present (and activated) when students are presented with process diagrams. Students who study process diagrams, teachers who use process diagrams for teaching biological processes and instructional designers who incorporate process diagrams in study material should anticipate this. Furthermore, scores on tasks with high cognitive demand were below average; we suggest that specific training on solving these type of problems and the interpretation of process diagrams in general might be needed. Finally, this study shows that even within a homogenous group (pre-university students with extensive biology training), variance in spatial ability factors accounts for individual differences in solving process-diagram problems. These students might particularly benefit from a training programme that includes a more strategic approach to interpreting process diagrams.

Note

1. The Surface Development Test correlated strongly, $r = .62$, $p < .01$ level (2-tailed), with the Choose a Path Test.

References

Baddeley, A. D. 1986. *Working Memory*. New York: Oxford University Press.

Bodner, G. M., and T. L. B. McMillen. 1986. "Cognitive Restructuring as an Early Stage in Problem Solving." *Journal of Research in Science Teaching* 23 (8): 727–737.

Buckley, B. C. 2000. "Interactive Multimedia and Model-Based Learning in Biology." *International Journal of Science Education* 22 (9): 895–935.

Canham, M., and M. Hegarty. 2010. "Effects of Knowledge and Display Design on Comprehension of Complex Graphics." *Learning and Instruction* 20: 155–166.

Chi, M. T. H., P. J. Feltovich, and R. Glaser. 1981. "Categorization and Representations of Physics Problems by Experts and Novices." *Cognitive Science* 5: 121–152.

Cook, M. P. 2006. "Visual Representations in Science Education: The Influence of Prior Knowledge and Cognitive Load." *Science Education* 90: 1073–1091.

Cook, M., G. Carter, and E. N. Wiebe. 2008. "The Interpretation of Cellular Transport Graphics by Students with Low and High Prior Knowledge." *International Journal of Science Education* 30 (2): 239–261.

Crowe, A., C. Dirks, and M. P. Wenderoth. 2008. "Biology in Bloom: Implementing Bloom's Taxonomy to Enhance Student Learning in Biology." *Cell Biology Education* 7: 368–381.

Ekstrom, R. B., J. W. French, H. H. Harman, and D. Dermen. 1976. *Kit of Factor Referenced Cognitive Tests*. Princeton: Educational Testing Service.

Guthrie, J. T., W. Shelley, and N. Kimmerly. 1993. "Searching Documents: Cognitive Processes and Deficits in Understanding Graphs, Tables, and Illustrations." *Contemporary Educational Psychology* 18: 186–221.

Hegarty, M. 1992. "Mental Animation: Inferring Motion from Static Displays of Mechanical Systems." *Journal of Experimental Psychology: Learning, Memory, and Cognition* 18 (5): 1084–1102.

Hegarty, M., and V. K. Sims. 1994. "Individual Differences in Mental Animation during Mechanical Reasoning." *Memory and Cognition* 22 (4): 411–430.

Kindfield, A. C. H. 1993. "Biology Diagrams: Tools to Think with." *Journal of the Learning Sciences* 3 (1): 1–36.

Kozhevnikov, M., M. Hegarty, and R. M. Mayer. 2002. "Revising the Visualizer-Verbalizer Dimension: Evidence for Two Types of Visualizers." *Cognition and Instruction* 20 (1): 47–77.

Kozhevnikov, M., A. Motes, and M. Hegarty. 2007. "Spatial Visualization in Physics Problem Solving." *Cognitive Science* 31: 549–579.

Kragten, M., W. Admiraal, and G. Rijlaarsdam. 2012. "Diagrammatic Literacy in Secondary Science Education." *Research in Science Education* November: 1–16.

Larkin, J. H., J. McDermott, D. P. Simon, and H. A. Simon. 1980. "Expert and Novice Performance in Solving Physics Problems." *Science* 208: 1335–1342.

Larkin, J., and H. Simon. 1987. "Why a Diagram is (Sometimes) worth Ten Thousand Words." *Cognitive Science* 11: 65–100.

Mayer, R. E., and R. Moreno. 2003. "Nine Ways to Reduce Cognitive Load in Multimedia Learning." *Educational Psychologist* 38 (1): 43–52.

Mayer, R. E., and V. K. Sims. 1994. "For Whom is a Picture worth a Thousand Words? Extensions of a Dual-Coding Theory of Multimedia Learning." *Journal of Educational Psychology* 86 (3): 389–401.

Miyake, A., N. P. Friedman, D. A. Rettinger, P. Shah, and M. Hegarty. 2001. "How are Visuospatial Working Memory, Executive Functioning, and Spatial Abilities Related? A Latent Variable Analysis." *Journal of Experimental Psychology: General* 130: 621–640.

Pribyl, J. R., and G. M. Bodner. 1987. "Spatial Ability and Its Role in Organic Chemistry: A Study of Four Organic Courses." *Journal of Research in Science Teaching* 24 (3): 229–240.

Reece, J. B., L. A. Urry, M. L. Cain, S. A. Wasserman, P. V. Minorsky, and R. B. Jackson. 2010. *Campbell Biology*. 9th ed. San Francisco: Pearson Education.

Schnotz, W., and M. Bannert. 2003. "Construction and Interference in Learning from Multiple Representation." *Learning and Instruction* 13: 141–156.

Schönborn, K. J., T. R. Anderson, and D. J. Grayson. 2002. "Student Difficulties with the Interpretation of a Textbook Diagram of Immunoglobulin G (IgG)." *Biochemistry and Molecular Biology Education* 30 (2): 93–97.

Sims, V. K., and M. Hegarty. 1997. "Mental Animation in the Visuospatial Sketchpad: Evidence from Dual-Task Studies." *Memory and Cognition* 25 (3): 321–332.

Sweller, J. 1994. "Cognitive Load Theory, Learning Difficulty, and Instructional Design." *Learning and Instruction* 4: 295–312.

Winn, W. D. 1993. "An Account of How Readers Search for Information in Diagrams." *Contemporary Educational Psychology* 18: 162–185.

Wu, H., and P. Shah. 2004. "Exploring Visuospatial Thinking in Chemistry Learning." *Science Education* 88 (3): 465–492.