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Uncovering cognitive processes: Different techniques that can contribute to cognitive load research and instruction

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ABSTRACT

This article discusses the use of different techniques for uncovering cognitive processes, for research and instructional purposes: verbal reporting, eye tracking, and concept mapping. It is argued here that applying these techniques in research inspired by cognitive load theory may increase our understanding of how and why well-known effects of instructional formats come about (e.g., split-attention, redundancy, or worked example effects) and refine or corroborate the proposed theoretical underpinnings of such effects. This knowledge can inform instructional design, and moreover, the effects of these techniques on learning can also be direct, by embedding the techniques in instruction.

1. Introduction

Research on instructional design inspired by cognitive load theory (CLT; Sweller, 1988; Sweller, Van Merriënboer, & Paas, 1998; Van Merriënboer & Sweller, 2005) usually includes assumptions on cognitive processes evoked by instruction that help or hinder schema acquisition. However, most often these assumptions are only tested by relatively indirect measures such as test performance data. It is argued here that *directly* studying cognitive processes during task performance and/or acquired cognitive structures after task performance can provide valuable information on *how* the effects of different instructional formats occur.

For example, CLT research has shown that split-attention instructional formats, such as separately presented but mutually referring text and diagrams, hamper learning, whereas integrated or multiple modality formats foster learning (Chandler & Sweller, 1991, 1992; Tindall-Ford, Chandler, & Sweller, 1997; see also Cierniak, Scheiter, & Gerjets, 2009). However, how these different instructional formats affect information processing and thereby learning is seldom studied directly, although there are many different ways in which learners can process for example text and diagrams (an exception is the study by Hegarty & Just, 1993, and some very recent studies, described in more detail in the section *Eye Movements for Studying Cognitive Processes*). For instance, they might first read the entire text, then look at the diagram, or look at the diagram every time a component is mentioned in the text, or first read a portion of text and then look at the diagram to verify understanding, et cetera (see also Hegarty & Just, 1993). Studying the way in which learners interact with text and diagrams in split-attention and integrated formats could show how and why the split-attention effect occurs, that is, exactly what process(es) lead to the extraneous load that hampers learning.

Next to providing more insight into how certain effects of instructional formats come about, more direct investigations of cognitive processes and acquired cognitive structures are also necessary for CLT to continue to extend its scope towards instructional design for advanced learners and the enabling of effective personalized instructional paths (see also Van Gog, Ericsson, Rikers, & Paas, 2005). When a learner's knowledge base changes, these changes influence the effectiveness of instructional formats during future learning. Hence, techniques to accurately judge the content of this knowledge base will help to adapt the instruction to the learner's needs (cf. Kalyuga, 2006a,b).

From a practical perspective, research using more direct investigations of cognitive processes and acquired cognitive structures can inform the design of more effective instructional materials and strategies (relatively *indirect* application). Moreover, techniques that uncover cognitive processes for researchers, can also do so for learners, which implies that these techniques might also be used *directly* to stimulate learning. For each of the three techniques discussed here, that is, verbal reporting, eye tracking, and concept mapping, the technique and the kind of information it elicits are first explained from a research perspective, then its potentials for learning and instruction are described.

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2. Verbal reporting

2.1. Verbal reports for studying cognitive processes

The two most widely used verbal reporting techniques are concurrent and retrospective reporting. Concurrent reporting (Ericsson & Simon, 1993; Van Someren, Barnard, & Sandberg, 1994) requires learners to verbalize all thoughts that come to mind *during* task performance. Retrospective reporting (Ericsson & Simon, 1993) on the other hand, requires learners to report the thoughts they had while they were working on a task *immediately after* task performance. Both techniques allow for valid inferences about the cognitive processes underlying task performance when the verbalization instructions and prompts are worded in such a way that the evoked responses do not interfere with the cognitive processes (e.g., learners should not be asked to reflect, explain or elaborate; see Ericsson & Simon, 1993, for information on appropriate instructions and prompts). An additional requirement for retrospective reporting to allow valid inferences is that task duration needs to be very short. On longer tasks there is a risk that information is omitted (i.e., thoughts that were present during task performance are not reported) or constructed (i.e., thoughts are being reported that were not actually there during task performance).

It has also been suggested that concurrent and retrospective reporting result in different types of information about cognitive processes. For example, according to Taylor and Dionne (2000), concurrent protocols seem to provide more information on actions and outcomes than retrospective reports, which seem to provide more information about strategies and conditions for actions than concurrent reports. Kuusela and Paul (2000) also reported that concurrent protocols contained more information on actions than retrospective protocols, arguing that retrospective reports often only contained references to the *effective* actions that led to the solution.

Both the risk of omission and construction in retrospective reporting, and the findings that concurrent and retrospective reporting seem to result in different types of information, seem to be related to the time at which the report is generated (during or after task performance). That is, the techniques rely on different memory systems. Whereas concurrent reports capture information available in working memory during the task performance process, retrospective reports require retrieval of memory traces of the task performance process from long-term memory when tasks are of longer duration (Camps, 2003; Ericsson & Simon, 1993; for a more detailed explanation of how this may affect information present in the reports, see Van Gog, Paas, Van Merriënboer, & Witte, 2005).

The fact that concurrent reporting relies on working memory may also have drawbacks. First of all, concurrent reporting may become difficult to maintain under high cognitive load conditions (Ericsson & Simon, 1993). Indeed, participants in the study by Van Gog et al. (2005) who experienced a high cognitive load during task performance (measured by self-reported investment of mental effort) indicated during a debriefing after the experiment that they disliked concurrent reporting and preferred cued retrospective reporting (see Van Gog, 2006). So, with novice learners or with highly complex tasks, concurrent reporting might not be the most optimal technique. Secondly, a lot of cognitive load research focuses on multimedia learning. On multimedia tasks that contain the same modality that the report draws on, reporting will interfere with information processing. For example, when instructional animations contain audio (spoken text, music, etc.), either concurrent reporting or understanding of the auditory information will be potentially compromised.

For these reasons, Van Gog et al. (2005) were looking for a method that did not have the drawbacks of concurrent and retrospective reporting. They proposed that cued retrospective reporting, in which a retrospective report is cued by a replay of a record of eye movements and mouse/keyboard operations made during the task (for an impression, see Fig. 1), might be a good candidate: Due to the retrospective nature of the report, problems of cognitive overload would not occur, whereas due to the cue, less omissions and constructions of actions would be expected than in ‘regular’ retrospective reporting. The presence of mouse and keyboard operations could stimulate reporting of thoughts regarding physical actions, whereas the added value of eye movements in the cue, is that they could trigger reporting of thoughts regarding purely cognitive actions.

Apart from being a useful research tool, verbal reporting techniques can also be directly or indirectly applied in the design of instruction.

2.2. Verbal reports in instruction

First of all, verbal reports of ‘experts’ could be used to design instruction. Learning by observing and/or imitating expert examples is a powerful learning strategy (Bandura, 1986). Cognitive load research has shown that worked examples, in which students can study a written account of an expert’s solution procedure, or process-oriented worked examples, in which the rationale behind the procedure is also made explicit, is very effective for novices (Van Gog, Paas, & Van Merriënboer, 2006, 2008; and for reviews of worked examples research Atkinson, Derry, Renkl, & Wortham, 2000; Sweller et al., 1998). The information to include in those examples can be obtained from verbal reports of experts (i.e., indirect use). Another option is not to provide students with a written account, but to use video-based or real-life modelling examples (cf., Zimmerman & Kitsantas, 2002; ; see also Wouters, Paas, & Van Merriënboer, 2008), in which students can observe the expert solving the problem while simultaneously verbalizing his/her thoughts (i.e., direct use of verbal reports).

It is important to note here, though, that expert is defined in different ways by different authors, and can mean someone who is good at performing a task, someone who has a lot of experience in a domain, or a teacher. ‘Experts’ as domain experts have a knowledge base that differs enormously from that of students both in magnitude and in organization, and they have developed automated procedures for solving routine problems in their domain (see Chi, Glaser, & Farr, 1988; Ericsson, Charness, Feltovich, & Hoffman 2006). Feldon (2007) showed that such experts’ self-reports are often suboptimal for instructional use, because automation may result in omissions. ‘Experts’ as good task performers, however, can also be well-performing students who are somewhat more advanced of the goal population, or teachers who are used to performing the task in the way it is taught to students. Verbal protocols of these ‘experts’, who have not yet automated performance procedures, are much closer to the knowledge base of the goal population of learners and could, therefore, be more effective.

Secondly, verbal reports generated by students themselves during instruction, may also enhance learning. For example, asking students to self-explain solution steps in worked examples or their own solution steps is known to enhance their understanding (Chi, De Leeuw, Chiu, & LaVancher, 1994). However, if students are not able to generate self-explanations, because they lack the necessary knowledge and as a consequence experience a high cognitive load imposed by the task, requiring them to self-explain may not help or even hinder learning (that is, rather than imposing germane load, it may lead to extraneous load for some learners). Moreover, self-explanations, however, are not always of the same nature/quality, which seems to be the determinant of effects on learning (Renkl, 1997). To enhance the quality of self-explanations, prompts can be used. For example, Atkinson, Renkl, and Merrill (2003) designed prompts to encourage learners to identify the underlying