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Medical students' cognitive load in volumetric image interpretation: Insights from human-computer interaction and eye movements

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ABSTRACT

Medical image interpretation is moving from using 2D- to volumetric images, thereby changing the cognitive and perceptual processes involved. This is expected to affect medical students' experienced cognitive load, while learning image interpretation skills. With two studies this explorative research investigated whether measures inherent to image interpretation, i.e. human-computer interaction and eye tracking, relate to cognitive load. Subsequently, it investigated effects of volumetric image interpretation on second-year medical students' cognitive load. Study 1 measured human-computer interactions of participants during two volumetric image interpretation tasks. Using structural equation modelling, the latent variable 'volumetric image information' was identified from the data, which significantly predicted self-reported mental effort as a measure of cognitive load. Study 2 measured participants' eye movements during multiple 2D and volumetric image interpretation tasks. Multilevel analysis showed that time to locate a relevant structure in an image was significantly related to pupil dilation, as a proxy for cognitive load. It is discussed how combining human-computer interaction and eye tracking allows for comprehensive measurement of cognitive load. Combining such measures in a single model would allow for disentangling unique sources of cognitive load, leading to recommendations for implementation of volumetric image interpretation in the medical education curriculum.

1. Introduction

Over the past two decades, cross-sectional image interpretation in medicine has shifted from using 2D images to volumetric images to diagnose patients. A volumetric image involves a volumetric medical scan, e.g., computed tomography [CT] or magnetic resonance imaging [MRI] that can be sliced up in many cross sections (i.e., 'slices') forming a stack of images. The user can scroll through a volumetric image from various angles and in various contrast settings, creating a 3-dimensional representation of the scanned structure. This shift has changed the task of medical image interpretation. A tiled set of 2D-images is static and contains less information than a volumetric image (Krupinski, 2011; Krupinski et al., 2012). Interpretation of volumetric images is more dynamic, involving an increase in both visual information processing and human-computer interaction (HCI, Andriole et al., 2011; Krupinski, 2010; Reiner, Siegel, & Siddiqui, 2003). Expert skill in image interpretation, including volumetric image interpretation, is crucial to avoid medical diagnostic errors (Donald & Barnard, 2012; Pinto et al., 2011), and thus volumetric images are now increasingly being used in medical education as well (Ravesloot, van der Gijp, et al., 2015; Rengier et al., 2013; van der Gijp et al., 2015).

Recent research in medical education highlights the effects this shift has had on students engaged in the image interpretation task. Radiology clerks take more time, and engage in more and different cognitive processes when interpreting volumetric images than 2D images (van der Gijp et al., 2015). Medical students report volumetric images to be more representative of clinical practice and perceive them to be easier to interpret than their 2D-counterparts.

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Interestingly though, performance of these students on interpretation of volumetric images was lower than on 2D images (Ravesloot, van der Gijp, et al., 2015; Ravesloot, van der Schaaf, et al., 2015).

A little studied aspect that may be particularly affected by volumetric image interpretation is students' cognitive load. Cognitive load, i.e., demand on human working memory, plays a pivotal part in the construction, elaboration, and automation of knowledge structures (i.e., schemas; Chi, Glaser, & Rees, 1982) in long-term memory (Sweller, van Merriënboer, & Paas, 1998; van Merriënboer & Sweller, 2005). Human's working memory capacity is limited and the cognitive load experienced is directly influenced by the information that the student needs to process and the schemas the student already possesses. A skilled student is better able to ignore task-irrelevant information and integrate new information with existing schemas and will therefore experience less cognitive load in a complex task than an unskilled student. Although cognitive load as a result from engagement in a learning task can be beneficial as it involves processing of task-relevant information, cognitive overload has shown to be detrimental for learning performance (Sweller, 2004; for an elaborate background on cognitive load theory in medical education, see van Merriënboer & Sweller, 2010). Previous research has identified relationships between cognitive load and visual information, simulated 3D environments, and human computer interaction in digital learning environments (e.g., Hollender, Hofmann, Deneke, & Schmitz, 2010; Mayer & Moreno, 2003; Ruiz, Taib, & Chen, 2011; Ruiz, Taib, Shi, Choi, & Chen, 2007; van der Land, Schouten, Feldberg, van den Hooff, & Huysman, 2013); however, to our knowledge little research is available in the context of medical image interpretation.

The present paper aims to shed light onto how volumetric image interpretation affects cognitive load experienced by medical students. Measures that indicate visual information processing and human-computer interaction are combined, and their common variance is used to predict cognitive load measures to: (1) investigate whether these measures can be utilised as indirect objective measures of cognitive load and, (2) to investigate how volumetric image interpretation by medical students affects their cognitive load.

1.1. Image interpretation in medical education

Medical image interpretation involves detecting and interpreting abnormalities in images of the human body for diagnostic purposes (Krupinski, 2010; Norman, Coblentz, Brooks, & Babcook, 1992; Taylor, 2007). Traditionally, assessment of students' image interpretation skills often involved interpreting single 2D images. In volumetric images, students do not examine one image to find a relevant structure, but must view a whole stack of slices, use an appropriate contrast setting, and in some cases adjust the angle to identify a structure. As a consequence they have to examine more information, inherently make more considerations regarding the relevancy of this information, while manipulating the image (Krupinski, 2010; van der Gijp et al., 2015). During image interpretation students have to cognitively link all the slices together in order to create a mental 3D representation of the body, which requires spatial skills and cognitive capacity of students (Krupinski, 2010; Stull, Hegarty, & Mayer, 2009). This increase in visual information and human-computer interaction when using volumetric images has been related to an increase in cognitive load in other contexts (van Merriënboer & Sweller, 2005).

Conversely, volumetric image interpretation may also decrease cognitive load. The possibility of examining the anatomical structure and its relative position from multiple angles can arguably provide the student with additional contextual information, i.e. the student does not need to infer the shape, size and position of a structure based on one 2D image (Ellis et al., 2006; Hegarty, Keehner, Cohen, Montello, & Lippa, 2007; van der Land et al., 2013). This contextual information allows for less specific prior knowledge needed for image comprehension (van Merriënboer & Sweller, 2010). As a result, it is currently unclear how volumetric image interpretation would affect cognitive load.

1.2. Measuring cognitive load in image interpretation

A wide variety of measures are utilised for measuring cognitive load, such as dual-task methodology (Brünken, Steinbacher, Schnotz, Plass, & Leutner, 2002), physiological measures (Antonenko, Paas, Grabner, & van Gog, 2010; DeLeeuw & Mayer, 2008; Nourbakhsh, Wang, & Chen, 2013), and self-report ratings (Kirschner, Paas, & Kirschner, 2009). However, these measures only provide a quantitative indication of cognitive load (Sweller, Ayres, & Kalyuga, 2011) but are uninformative of what causes this cognitive load. Using indirect objective measures that are specific to the (volumetric) image interpretation task, and relate these to validated subjective and physiological measures for cognitive load (e.g., DeLeeuw & Mayer, 2008) may address this (Martin, 2014). Indirect objective measures are direct reflections of task behaviour that bear a relationship with cognitive load, but this relationship may be mediated or moderated by other variables such as skill or task-performance (Brünken, Plass, & Leutner, 2003). If common variance of image interpretation task-specific objective measures has a relationship with validated measures of cognitive load while taking into account mediators and moderators, this would support using these measures for disentangling cognitive load in image interpretation. The nature of each of the contributing measures can then highlight what aspects of the task are related to cognitive load.

1.3. Approach

In the first study, variables are calculated from recorded human-computer interaction of participants engaged in volumetric image interpretation tasks. Logging participants' interactions within the learning environment reveals how many slices are displayed due to scrolling through the image, how many viewing angle changes are made, how long it takes to locate the relevant slices, how much time is spent on relevant vs. irrelevant slices, and how long a student takes to finish a task (Vincken & Ravesloot, 2010). Although time to finish a task has been previously related to various types of cognitive load in other contexts, the usage of this data in this context is new and effects on cognitive load are unknown (Brünken et al., 2003). As human-computer interaction variables are only conceptualised as indirect objective measures of cognitive load, other potential factors in these relationships must be considered. For example, it should be acknowledged that experts are better in deciding which information is relevant than novices (Eva, Norman, Neville, Wood, & Brooks, 2002; Lesgold et al., 1988; van Gog, Kester, Nievelstein, Giesbers, & Paas, 2009), and are quicker to find abnormalities in medical images (Kok et al., 2015). Although the medical students participating in the current study are all at similar stages of their training, performance differences caused by differential skill development are likely. As a result, there is a potential influence of performance on the relationship of information exposure and cognitive load (Brünken et al., 2003). The first study therefore includes a measure of test-performance in image interpretation to control for this and to investigate a potential moderation in the relationship between human-computer interaction and cognitive load.

In a second study, eye tracking is used to provide more in-depth information on what a medical student examines while