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Learning and assessment with images: A view of cognitive load through the lens of cerebral blood flow

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Abstract

Understanding the relationship between cognitive processing and learner performance on tasks using digital media has become increasingly important as the transition towards online learning programs increases. Determining the impact of implementation of instructional resources is often limited to performance outcomes and comparisons to the status quo. This study measured changes in cerebral blood velocity (CBV) of the right middle cerebral artery during visual learning tasks using static images. Transcranial Doppler ultrasonography was used to compare the changes in CBV during learning of individuals with high and low spatial ability. Our results show that there is a slight increase from baseline values of CBV in individuals with high spatial ability during the learning task for the present study. In contrast, individuals with low spatial ability experience a decrement from baseline during the learning task. These results suggest spatial ability mitigates cognitive load and potentially has an impact on learner performance on visual learning tasks.

Introduction

The often-used adage that a picture is worth a thousand words may have some scientific validity when one considers the prevalent use of images for learning, and how images may impact the learner. The use of media and specifically images for learning has been studied considerably in recent years (Ozcinar, 2009). Studies related to the use of images for learning have produced various design principles (Mayer, 2002, 2008, 2010; Mayer, Hegarty, Mayer and Campbell, 2005). These principles are based on a learner's limited capacity to hold information in short-term memory (Reed, 2006; Sweller, 2003). For example, Mayer *et al.* (2005) recommend that the use of images and accompanying text should remain in close proximity to one another to reduce extraneous load in something they termed the *spatial contiguity effect*. It is speculated that these design principles can directly affect learner cognitive load and thus student performance (Ayres and

Practitioner Notes

What is already known about this topic

- Spatial ability is related to student performance when learning with different types of images
- Theoretical construct for cognitive load has been well established and reported in the literature.
- Cognitive processing can be measured via transcranial Doppler ultrasonography.

What this paper adds

- Novel data to illustrate the relationship between cerebral blood velocity and spatial ability
- Methodological approaches to study the relationship between cognitive processing and performance
- A report on the implications of using images for learning and how this is mitigated by spatial ability.

Implications for practice and/or policy

- This paper contributes further to design principles for the use of images in learning materials to mitigate learner cognitive loads
- Cognitive effort, as measured by cerebral blood flow, of low spatial ability learners is very different than that of high spatial ability learners using static images
- Spatial ability plays an important role for effective use of media in learning.

Paas, 2007; Paas and Kester, 2006, Paas, Renkl & Sweller, 2004; Verhoeven, Schnotz and Paas, 2009); however, the effect of image use measured from a physiological perspective is not yet fully addressed in the literature (Mayer, 2010; Tomasi, Chang, Caparelli & Ernst, 2007).

Research consistently demonstrates that a learner's ability to mentally manipulate images mitigates the burden of cognitive load (Meijer & van den Broek, 2010; Nguyen, 2012; Nguyen, Nelson & Wilson, 2012). This ability is referred to as spatial ability and can be defined as a cognitive ability to generate, retain, retrieve and transform well-structured visual images (Lohman, 1996). Levels of spatial ability have been determined by using one of two commonly used tests: the mental rotations test developed by Shepard and Metzler (1971), or the redrawn version develop more recently by Peters *et al.* (1995). In both instruments, proficiency in mental rotation has been used as a determinant of one's spatial ability.

In spite of research related to the use of media for instructional purposes (Khalil, Paas, Johnson & Payer, 2005; Lowe, 2004), there is little evidence that highlights the relationship between learning with technology, the physiological response and the impact on learning outcomes. Whelan (2007) suggested that neuroimaging would help guide our understanding of cognitive load. However, the use of neuroimaging overlooks the critical element of temporal sensitivity and it is for this reason the present study used transcranial Doppler ultrasonography (TCD) to examine cognitive load.

Due to limited capacity for energy storage (Brown & Ransom, 2007) and the high metabolic rate of brain tissue compared to others tissues in the body like bone, muscle or fat, precise coupling of cerebral blood flow is critical for maintenance of constant nutrient and oxygen supply to the brain (Willie *et al.*, 2011) in order to maintain conciousness and respond to stimuli in our environment. The use of TCD as a benign and non-invasive technique to monitor brain blood flow velocity in major cerebral vessels is well prescribed (Aaslid, Markwalder & Nornes, 1982) and is used in a variety of situations where information regarding brain blood perfusion (Duschek & Schandry, 2003; Wilson, Serrador & Shoemaker, 2003). Under all but extreme situations, cerebral blood flow velocity is directly proportional to blood flow in large arteries supplying cortical tissue. Blood flow changes in rapid temporal relation to oxygen consumption, like mental processing. Depending on the cerebral vessel under investigation, the middle cerebral artery (MCA) for example, blood velocity across individuals (mean age 36, range of 20–56) was 62 ± 12 cm/s (mean ± standard deviation), with a range of 33–90 cm/s (Aaslid, 1987; Willie *et al.*, 2011). Age and sex do contribute to variability with general decreases in cerebral blood flow over the age of 40 years (Krejza *et al.*, 2005). Due to variability in measures across individuals, researchers often avoid reporting raw velocity values (cm/s) but calculate the relative percentage changes from individual baseline blood velocities in order to make comparisons across groups and individuals. Given the non-intrusive nature coupled with the high temporal resolution of TCD, it represents an ideal measurement modality for educational research where indications of participant cognition are required.

Although multimedia learning resources take on many forms and the use of media can be directed at a multitude of functions, we are concentrating effort on characterizing how learners with differing spatial abilities respond to images, in particular static images that do not have any inherent dynamism. The present study examined learner physiological changes that occurred when static images were used for learning and subsequent assessment. This study provides evidence that can inform designers how the use of technology, and images therein, impacts learner cognition and potentially learning outcomes. Further, the results presented here add to cognitive load research by providing quantifiable values to the notion of "load" and what that load looks like in the learner through the lens of cerebral blood flow. The results from the present study offer an expansion to our understanding how cognitive load induced by images may be mitigated.

Methods

Functional neuroimaging technologies have great appeal for studies related to cognitive processing (Weisberg, Keil, Goodstein, Rawson & Gray, 2007). Neuroimaging technologies like functional Magnetic Resonance Imaging hold great promise for understanding the behavior of the brain during different learning processes. However, the use of this technology for educational research is premature and often fraught with misconceptions about the results obtained (Dekker, Lee, Howard-Jones & Jolles, 2012; Goswami, 2006; Sweller, 2010).

The approach taken in this study was to investigate changes in the cortical demand for blood resulting from cognitive processing in a larger, more generalized, region of the brain responsible for interpretation of visual information. We focused on temporal changes in blood flow within a cerebral region resulting from the learning exercise, rather than absolute localization of specific active regions. This approach guided the choice to use TCD as it is more sensitive for measurements of temporal changes in cognitive processing (Aaslid, 1987; Aaslid *et al.*, 1982; Bakker *et al.*, 2014; Boban, Črnac, Junaković, Garami & Malojčić, 2014; Cupini *et al.*, 1996; Deppe, Knecht, Lohmann & Ringelstein, 2004; Payne, Gutierrez-Sigut, Subik, Woll & MacSweeney, 2015; Schmidt *et al.*, 1999, Stroobant & Vingerhoets, 2000).

Participants

Twenty-nine healthy adults (aged 18–51, Mean 29 ± 8.8 years) participated in the study. Participants volunteered for the study via in-class announcements and online announcements in their course websites. Ten females and nineteen male participated in the study. The recruitment protocol was reviewed and approved by the ethics review board at the institution where the study was conducted. All participants were screened to ensure right-hand dominance using the Edinburgh

Handedness Inventory (Oldfield, 1971). This is a standard procedure to ensure lateralization of neurological functioning (Aaslid *et al.*, 1982, Kelley *et al.*, 1992; Stroobant & Vingerhoets, 2000). All participants had normal or corrected-to-normal vision and were not colorblind (so as to see the structures of the test models and identify them by color rather than anatomical name). It was confirmed that all participants had abstained from consuming caffeine at least six hours prior to testing to ensure there was no confounding influence on cardiovascular or blood flow velocity indices.

Apparatus

Beat-by-beat measurements of transcranial cerebral blood velocity (CBV) of the right Middle Cerebral Artery (rMCA) were acquired in a sitting position with hands on a desk using a 2-MHz pulsed TCD ultrasound probe (Neurovision system, Multigon Industries, Elmsford, CA, USA). Breath-by-breath end-tidal CO_2 ($etCO_2$) was calibrated for atmospheric air pressure, and measured (CAPSTAR 100, IITC Life Science Inc. Woodland Hills, CA, USA) using a nose/mouth mask. One-way valves in the mask prevented atmospheric air from mixing the exhaled air of participants. All collected data was collected using a data acquisition device (PowerLab 16/35, ADInstruments Inc., Colorado Springs, CO, USA), and analyzed using analysis software (LabChart, ADInstruments Inc., Colorado Springs, CO, USA).

Tests

1. Edinburgh *Handedness Inventory*—Since lateralization of cognitive function is indeterminate in individuals deemed to be left-hand dominant, the Handedness Inventory (Oldfield, 1971) is often employed to determine candidate suitability in studies where localization of cognitive function is required.
2. *Mental Rotations Test (MRT)*—A redrawn version of the Vandenberg and Kuse (1978) MRT developed by (Peters *et al.*, 1995). The MRT is used to measure the ability of individuals to mentally rotate a three-dimensional (3D) object. The mental rotations test is often used to measure the spatial ability of individuals, which has been demonstrated to

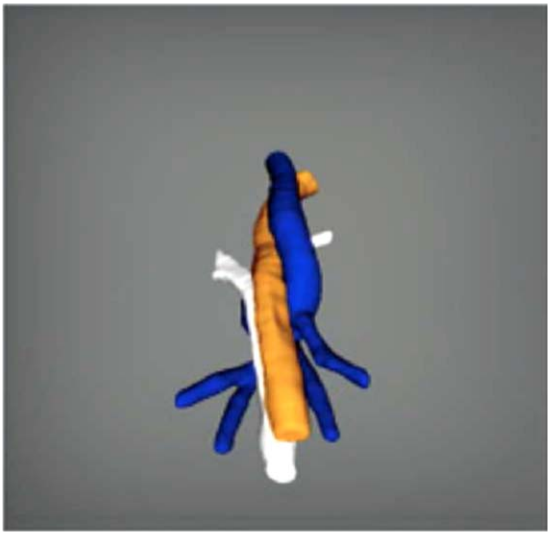

Figure 1: Spatial anatomy test (SAT) Model illustrating one picture from a series of 12 shots demonstrating the aorta, esophagus and trachea of the human thorax. Each of the 12 static pictures were presented in various positions about the orthogonal planes

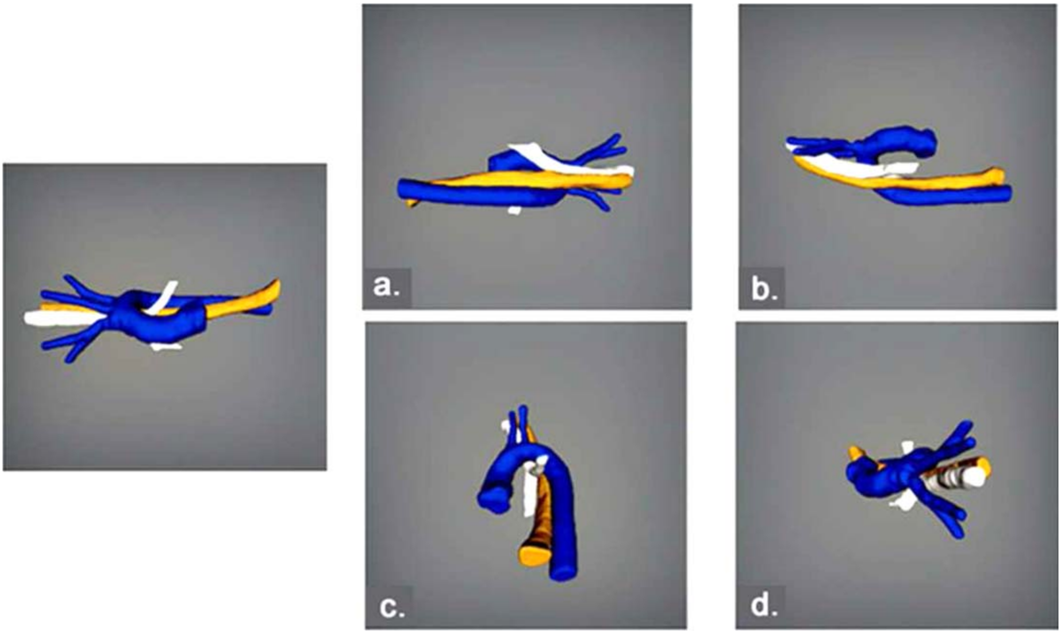

Figure 2: Example of the SAT 1 question set. In this case, the two correct answers that are identical to the exemplar are boxes a and c

have an impact on learning with complex images (Khalil *et al.*, 2005; Lowe, 2004; Meijer & van den Broek, 2010).

3. *Spatial Anatomy Test (SAT)*—The SAT was developed for previous research by Nguyen *et al.* (2012). The test requires participants to study a 3D model that consisted of three intertwined anatomical structures (see Figure 1).

   The SAT model is presented as a series of still images taken from different perspectives. Participants are asked to study the image (eg, spatial arrangements, location or proximity of each structure to one another) for a period of 2 minutes. The model is presented to the participant as a series of 12 images taken from different perspectives, each perspective shown for a total of 10 seconds. Following the learning period, participants are given three assessments consisting of 10 questions each. Examples and descriptions of these assessments are presented below.

   The first assessment task of the spatial anatomy test (SAT 1) is akin to the MRT. This test requires participants to mentally rotate the model to match a presented target perspective. The participant is presented with four options and must select two of the four that could be rotated to match the target object in the given perspective (see Figure 2). Scoring is based on the ability of the participant to select both correct options.

   The second assessment task (SAT 2) required participants to determine what a cross-section or slice of the model will look like given a particular plane and direction (see Figure 3). For this test, participants were provided with four possible choices and they must select the correct option. There is only one correct choice and, therefore, no partial points are awarded.

   The final assessment task (SAT 3) is a complementary assessment to task two. For this task, the participants were presented with a series of possible planes intersecting the model. A target perspective of an intersecting plane is presented and the participant must select which plane this perspective is taken from (see Figure 4). A direction arrow is

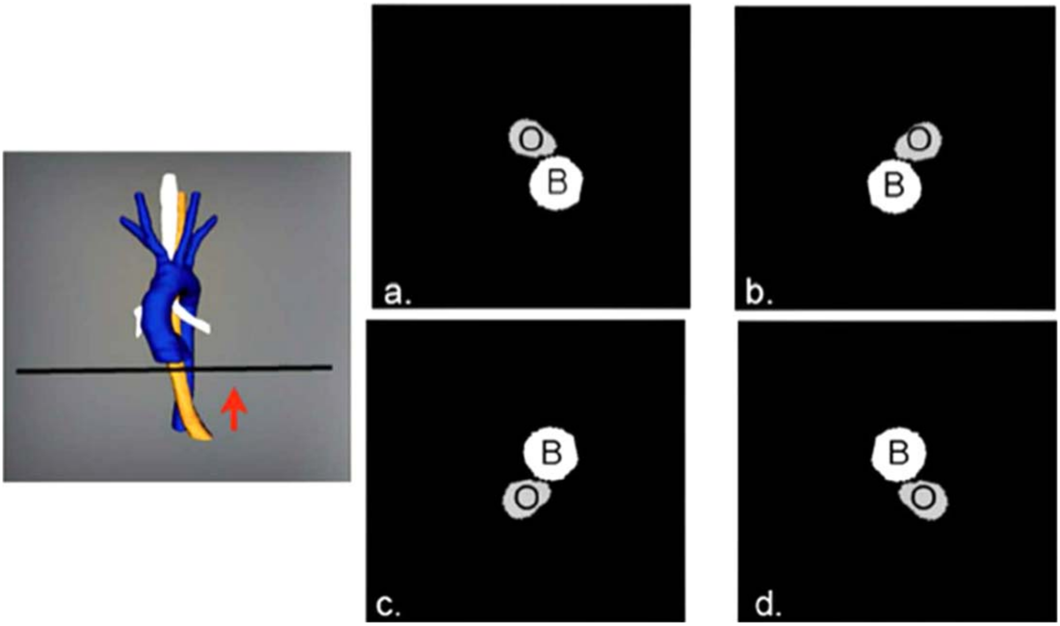

Figure 3: Example of the SAT 2 question set. Here, the cross section in box a is referring to the correct slice from the exemplar image. Please note that O and B refer to tube colors

provided to indicate which direction the participant is looking toward. Again, only one correct response is available, and no partial marks are awarded.

4. *Human Ankle Test (HAT)*—This test was modeled after previous work by Garg, Norman, Spero and Taylor (1999). Where they used a spatially simple model of wrist bones, we used the ankle. Like the SAT above, the HAT required participants to study a series of 12 static images of various perspectives of a model of the human ankle (see Figure 5). Each image was presented for a total of 10 seconds, or 120 seconds total learning time. The participants were asked to focus on the orientation, position and proximity of the colored bones rather than learning the names (fibula, tibia, talus, calcaneus, cuboid, navicular and the medial, intermediate and lateral cuneiform). All references and assessments would be based on orientation to the colored structures.

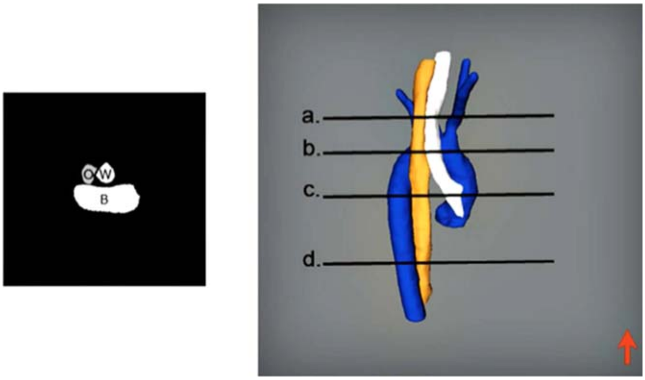

Figure 4: Example of the SAT 3 question set. Here, the exemplar slice is indicative of slice b from the image. Please note O, W, B refer to tube colors

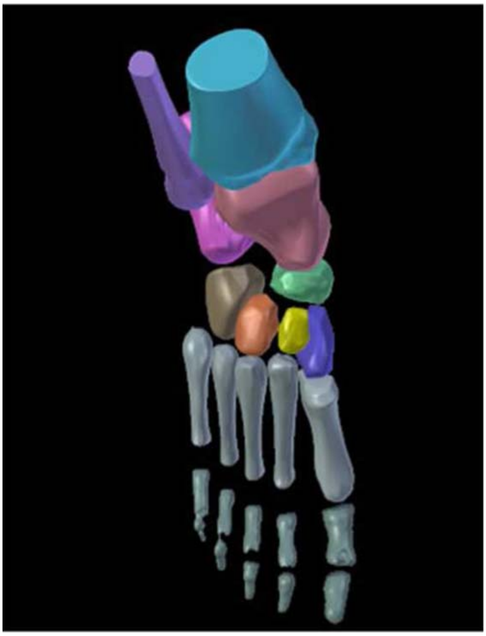

Figure 5: Human ankle test (HAT) model illustrating a single picture from a series of 12 shots demonstrating the osteology of the human ankle in stylized format. Each of the 12 static pictures is presented in various positions; the current picture is a superior view of the right foot

The HAT was designed to reflect similar testing strategies as those used in the SAT. Therefore, there are similarities in the question formats of both instruments. However, in some of the HAT assessments (HAT 2–3), greater demands on working memory are employed in concert with participant's spatial ability to correctly answer questions. The first assessment task of the Human Ankle Test (HAT 1) was a pure mental rotations type task like that of the MRT. Participants were presented with a target perspective of the human ankle model and a series of four options (see Figure 6). The participant had to select two of the four options presented that could be rotated to match the target perspective. Points were only awarded if the participant identified both correct options.

The second assessment task (HAT 2) employed a similar method as outlined in earlier work by Garg *et al*. (1999). Here, the bone model was obscured by skin and participants had to identify the bone that was indicated by a marker (red dot) (see Figure 7). To assist the participant a sample of the colors was provided as well as a schematic representation of the bones of the human ankle. Participants had to identify the bone by color. There

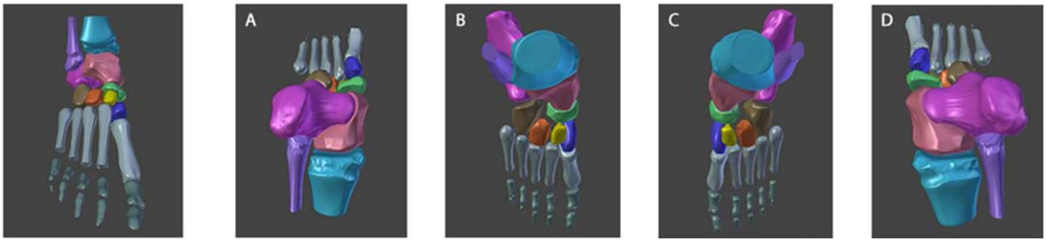

Figure 6: Example of the HAT 1 question set. The participant will focus on one reference bone to use as a guide for mental navigation. The two figures that match the exemplar are image a and b

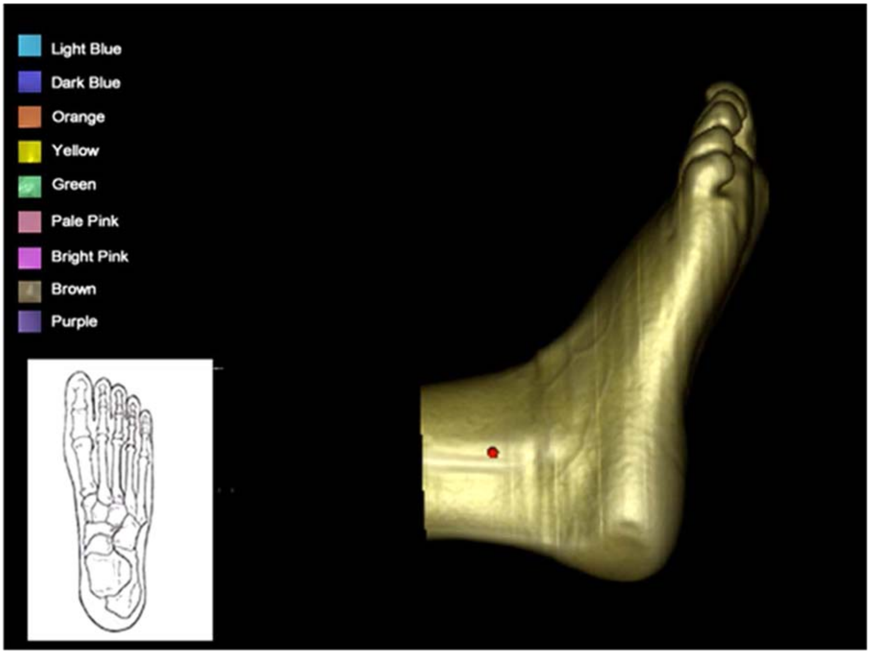

Figure 7: Example of the HAT 2 question set. The red dot is indicates the underlying purple bone from the model used during the learning phase of the test (Figure 6)

were no partial marks for closely identifying the bone, only for correctly identifying the bone.

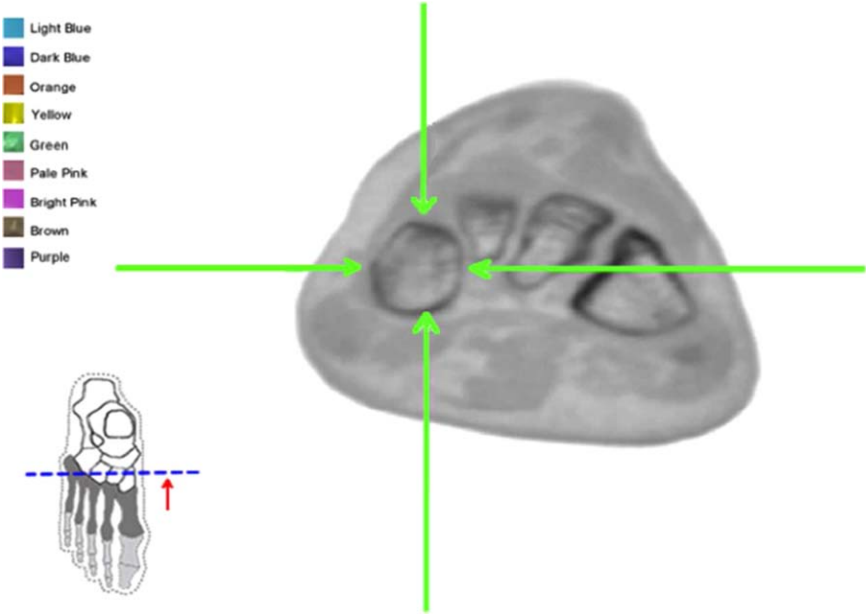

Figure 8: Example of the HAT 2 question set. The markers are indicating the brown bone from the model used in the learning phase

The third and final test (HAT 3) was designed to impose an increased burden on working memory for the learner. This was accomplished by removing more contextual cues from the question. In this set of questions, the participant is given a cross-sectional slice of the model and informed of the direction the plane of the slice. The participant is then asked to identify the bone color indicated by markers (see Figure 8). Again, a single point was only awarded when the participant correctly identified the bone color.

Procedure

The data collection process for the present study occurred in several stages. A schematic of the procedure is presented to illustrate the protocol for the present study (see Figure 9). The general protocol can be separated into two general phases; pretesting procedures and test procedures. Each will be discussed in detail below.

Pretest procedures

Participants completed the redrawn Vandenberg & Kuse (1978) MRT developed by Peters *et al.* (1995) as the preliminary step in the study. This task was completed online following the protocol outlined by Peters *et al.* (1995). Participants were then sorted into a high or low spatial ability group by a median split depending on their relative scores upon completion of the MRT task. A median split allowed for separation of participants into equal groups; high or low spatial ability, based on relative standing within the pool of participants. Another test, the *Edinburgh Handedness*

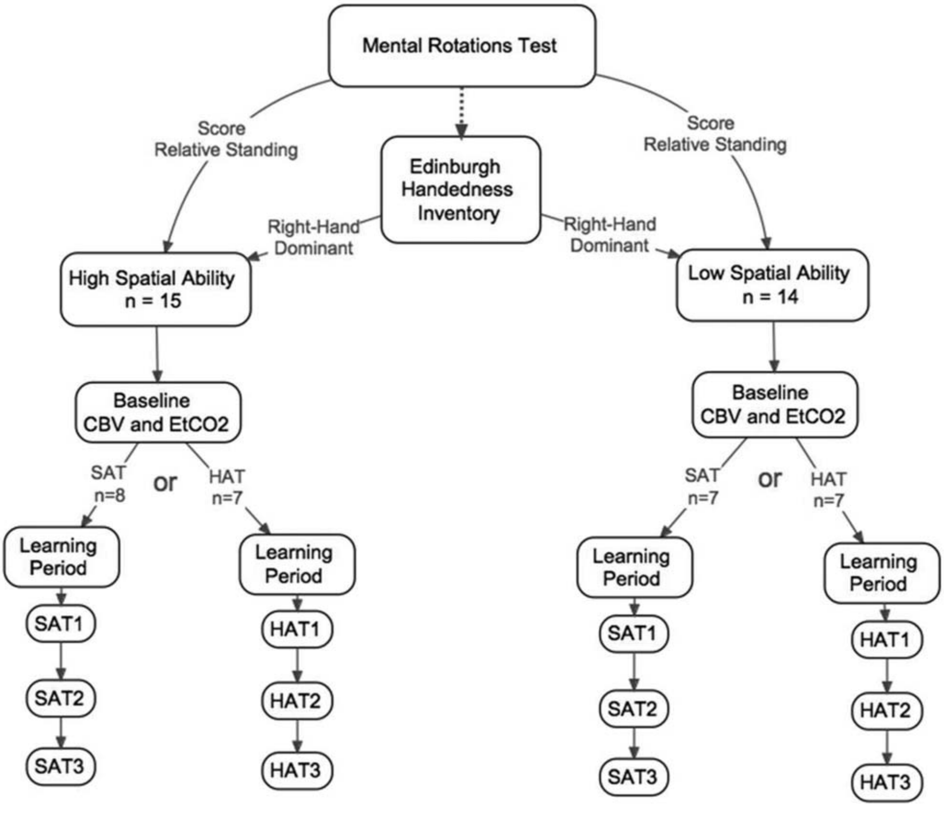

Figure 9: Research protocol schematic. The schematic shows how participants were grouped and the sequence of human ankle tests (HAT) or spatial anatomy tests (SAT) that each participant completed during this study

Inventory, a commonly used instrument to determine the dominant hand or handedness of participants (Oldfield, 1971) was also given as a pretest measure to ensure the viability of each participant. The present study required right-hand dominant participants, excluding left-hand dominant individuals because lateralization of neurological function is indeterminate in individuals who are left-hand dominant. For the present study no individuals were excluded as all were determined to be right-hand dominant.

Following the categorization based on spatial ability and determination of suitability based on handedness, baseline measures of $etCO_2$ and CBV in the rMCA were taken for each individual. Each participant was instructed to focus on a static image (star), while the above mentioned physiological variables were recorded for a period of 30 seconds. This served as a within subject comparison to measure changes in physiological response during the testing procedures.

Testing procedures

Participants were randomly assigned one of two models, the SAT (see Figure 1) or the HAT (see Figure 5). Throughout the testing procedures, mean CBV of the rMCA was recorded using TCD. The M1 segment of the rMCA was the focal point for measuring changes in cognitive processing during the testing phase. Prior research illustrates that the perfusion of regions supplied by the rMCA are critical for visual spatial interpretation during cognitive tasks (Aaslid *et al*., 1982; Cupini *et al*., 1996; Deppe *et al*., 2004; Schmidt *et al*., 1999; Stroobant & Vingerhoets, 2000). Additionally, $etCO_2$ was measured to ensure that changes in CBV were limited to cognitive processing rather than changes in respiration (Kelley *et al*., 1992) as declines in arterial CO_2 affect downstream cerebral arteriole diameter and blood flow measures (Duschek, Werner, Kapan & Reyes del Paso, 2008).

Physiological data and participant test responses were collected for each of the three sets of questions as described in Figure 9. The data collection and sorting procedure for each participant was consistent and is outlined in the proceeding section.

Data sorting and statistical analysis

The SAT and HAT were administered using the institution's Learning Management System, *Sakai* (*Sakai CLE, Apereo Foundation 2012)*. During both HAT and SAT testing sessions the first author took field notes observing the participant and recording the responses using the comment feature in recording software, *LabChart*. A code for each question was added to the recorded physiological data so that test responses and timings could be paired with collected test data collected in *Sakai*. These two sets of data were combined into a single spreadsheet for analysis purposes. The combination enabled comparison of testing performance and timing with individual physiological variables across participants of high and low spatial ability.

In order to convert continuous measures of $etCO_2$ and CBV into time segments indicative of mental processing, 3–4 seconds of continuous data was sampled preceding each subjects' response for each question on each of the SAT and HAT tests. Average values of peak $etCO_2$ and mean CBV were then calculated for instance. Comparison of performance results and changes in CBV were conducted using a one-way ANOVA. Baseline physiological measures for high and low spatial ability groups were compared using a *t*-test. Differences in percent change in CBV from each individual's baseline among high and low spatial ability learners was critical for understanding how learners differ in physiological response and to enable comparison across individuals. Further comparison of physiological response during correct and incorrect answers was also conducted. Correct/incorrect comparisons were done to investigate physiological changes according to performance.

Table 1: Spatial ability, sex and mean score matrix

	Male	*Female*	*Mean MRT score*
High spatial ability	13	2	16.4 ± 1.92
Low spatial ability	6	8	10.3 ± 2.65

Table 2: Baseline values for etCO2 and CBV in high and low spatial ability groups

	etCO$_2$ mmHg	*CBV cm/s*
High spatial ability	35.1 ± 10.5 mmHg	64.1 ± 5.1 cm/s
Low spatial ability	30 ± 12.6 mmHg	62.1 ± 10.3 cm/s

Results

The 29 participants (10 female/19 male) were assigned to either the high or low spatial ability group based on their relative standing following completion of the MRT. The results of the mental rotations test are presented in Table 1.

Baseline

In order to determine the extent of the changes that resulted from learning with static images, baseline values were collected for both the right middle cerebral artery blood velocity (CBV) and etCO$_2$. The obtained mean baselines for both the high and low spatial ability groups are presented in Table 2.

When the baseline values of CBV for the high and low spatial ability groups were compared, no differences between groups were detected ($t(26) = 0.3983, p > 0.05$). Similarly, there were no differences in baseline etCO$_2$ between groups ($t(26) = 0.9898, p > 0.05$). As considerable variability

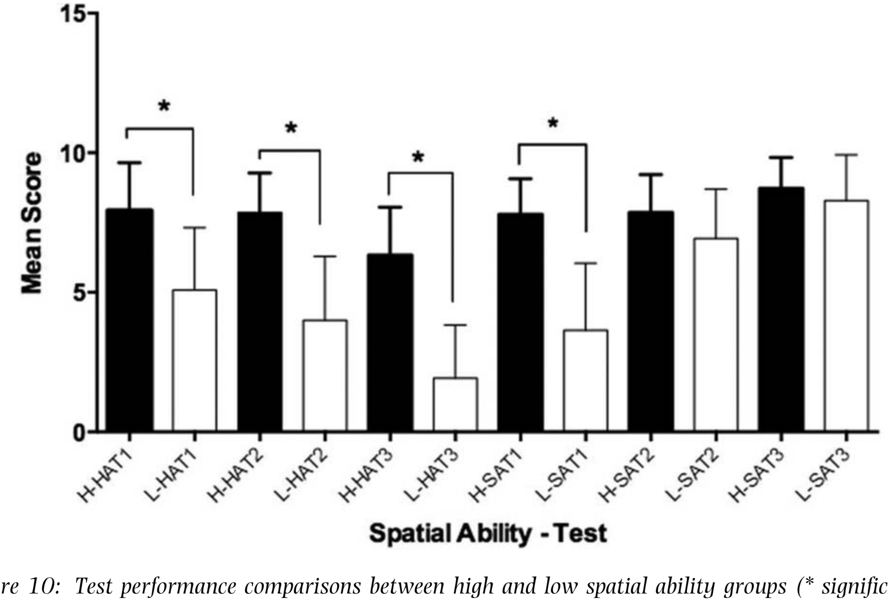

Figure 10: Test performance comparisons between high and low spatial ability groups (significant at $p < 0.0001$). Here, the numbers following the SAT and HAT refer to assessment types while the H- and L- preceding indicate high or low spatial ability*

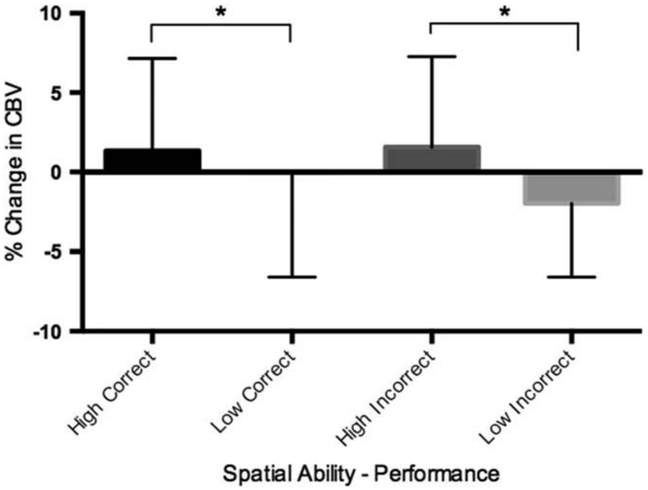

Figure 11: Mean percent changes in mean CBV during correct and incorrect responses by high and low spatial ability learners (significant at $p < 0.05$)*

occurs across individuals, baseline values were calculated for each participant and used to determine the magnitude of changes in both CBV and $etCO_2$.

Test performance

For the present study, we used performance (test scores) as the variable of interest to correlate with physiological response. Performance results for learning with static images in both high and low spatial ability groups are presented in Figure 10. In each phase of the HAT and SAT test subdivisions, the maximum score is 10. The difference in performance between high and low spatial ability groups on the various tests (HAT 1 through HAT 3 and SAT 1 through SAT 3) was deemed to be significant [$F(7, 1743) = 4.626, p < 0.0001$].

Participant accuracy categorized by spatial ability is shown in Figure 10. The results from the HAT tests (HAT 1 through HAT 3) indicate a difference in performance when comparing individuals with high (H) spatial ability to individuals with low spatial ability (L) ($p < 0.001$. A similar difference was also found on the first SAT 1 ($p < 0.0001$). No significant difference was found between high and low spatial ability groups on SAT 2 and SAT 3 ($t(54) = 1.78, p = 0.162$).

Physiological responses

CBV responses for each participant were normalized to individual baselines (see Table 2). Compared to baseline, mean percent changes in CBV were positive in high spatial ability individuals (1.4% ± 5.7) while individuals of lower spatial ability had negative CBV changes (−0.9% ± 5.8). Accounting for answer accuracy (getting the question correct or not), high spatial ability learners demonstrated increases in CBV during both correct (1.3% ± 5.8) and incorrect responses (1.6% ± 5.7). Conversely, low spatial ability learners demonstrated decreases in CBV during both correct (−0.04% ± 6.6) and incorrect (−2.0% ± 4.6) responses (see Figure 11).

Changes in $etCO_2$ were compared between high and low spatial ability groups. During testing $etCO_2$ did not change significantly ($t(255) = 1.206, p = 0.1158$). The relatively stable result enables us to determine changes in CBV are related to cerebral metabolism and not a result of changes in respiratory alterations.

Discussion

The results from the present study highlight two critical issues. First, we provide evidence that high and low spatial ability individuals perform differently during "short term recall testing" when using static images as the primary resource for learning and assessment. Second, the differences in performance in our testing paradigms are accompanied by significant cerebral blood flow differences between these two groups.

The differences in CBV demonstrated amongst high and low spatial ability participants are some of the first evidence of this type. At the onset of this study, it was speculated that high spatial ability learners might demonstrate a form of efficiency through superior test performance with relatively lower CBV compared to their lower spatial ability counterparts. Our results indicate a clear difference whereby high spatial ability learners show a marked *increase* in CBV compared to their low spatial ability counterparts. Rympa and D'Esposito (1999) found that differences between fast and slow individuals on cognitive tasks resulted in varied processing in different regions of the brain. This group concluded that individuals who are less proficient in a task showed increased activity in the prefrontal cortex whereas more proficient individuals showed a decrease in prefrontal cortex activity when compared to a baseline measure. The conclusions of Rympa and D'Esposito (1999) are intriguing given the results presented here. The present study was concerned with blood flow responses to support cognitive processing from a magnitude and temporal perspective rather than a geographic perspective. That is, we were primarily interested in global changes in blood flow to a large area of the right cerebral cortex, rather than locating the specific cortical regions where activity levels were highest. We found that learners with lower spatial ability generally had lower blood velocity in their rMCA. Based on the results from other studies (Gould, Brown, Owen, Ffytche & Howard, 2003, Jaeggi *et al.*, 2007; Rypma, Berger & D'Esposito, 1999; Smith & Jonides, 1997; Tomasi *et al.*, 2007) we could theorize that blood flow may be shunted to other cortical areas outside the rMCA irrigation territory in low spatially able individuals, resulting in relatively lower MCA velocity but potentially increased velocity in another artery. Based on the findings in the present study, we would predict that lower spatial ability individuals would demonstrate an increase in CBV in their Anterior Cerebral Artery, the artery that supplies the prefrontal cortical region. The prefrontal region is believed to be more active during situations where cognitive load taxes working memory or decision making (Rypma *et al.*, 1999; Sandrini, Rossini & Miniussia, 2008; Tsujimoto, Yamamoto, Kawaguchi, Koizumi & Sawaguchi, 2004; Zang *et al.*, 2005). This hypothesis remains to be tested with spatial ability as the differentiating criteria, and may be the focus of a future investigation.

A potential limitation to the approach of the present study is that the learning materials examined the use of static images with little in the way of the extraneous material required for learning and testing. In particular, the ankle test (HAT) used for measuring performance required individuals to identify structures by color rather than anatomical nomenclature. However, the model required participants to focus on roughly seven or less structures to fall within the theorized limits of working memory (Baddeley, 1986; Huk, 2006; Miller, 1956). It is unknown how commonly used models with interactive components and additional and potentially extraneous information would affect the learners. Cognitive Load literature would suggest that additional information would potentially exacerbate the physiological data collected within the present study (Mayer & Moreno, 1998, 2003; Moreno & Mayer, 2007; Reed, 2006; Rummer, Schweppe, Scheiter & Gerjets, 2008; Tabbers, Martens & van Merrienboer, 2004). Additional research that builds on the present study is needed to ascertain the effects of different image types on the CBV of individuals with high and low spatial ability.

In terms of design principles and the application of technology to teaching and learning, the present study offers some considerations. First, the results highlight that spatial ability has an impact on effective use of relatively simple images for learning and assessment. We indicate simple images given that similar images in an anatomical context would typically incorporate additional visual information like (labels, leaders, functional vignettes) adding to both extraneous and intrinsic cognitive loads imposed on the learner. Further, the results obtained here demonstrate that regardless of performance, cognitive processing demands, as indicated by different cerebral blood flow, are different based on spatial ability and this ability seems to be related to overall performance. Finally, as in the case of SAT 2 (see Figure 3) and SAT 3 (see Figure 4), the addition of cues or aids seems to help mitigate the effects of cognitive load in both high and low spatial ability learners. In that regard, the performance outcomes were not significantly different between the spatial ability groups. This finding allows us to make some recommendations for the use of images. That is, in order for images to be effective for all learners, cues and aids need to be incorporated. In the case of complex models, alternative perspectives could aid learners who are challenged by lower levels of spatial ability. This same recommendation has often been presented in cognitive load research in the form controls and pacing (Harskamp, Mayer & Suhre, 2007; Hasler, Kersten & Sweller, 2007; Wouters, Tabbers & Paas, 2007). Therefore, the inclusion of learner-controlled perspectives could be the best strategy to effectively incorporate images into a learning environment or task.

Conclusion

The present study serves as a starting point to investigate further how direct physiological measures can be indicative of cognitive load. We identified significant cerebral blood flow differences exist between high and low spatial ability learners during the use of relatively simple images in a learning task. This information may aid in developing learning materials to support individuals with lower spatial ability as this has been shown to have an impact on learner performance (Nguyen, 2012; Nguyen *et al.*, 2012). Practical recommendations to support learners could include the development of training tools to increase spatial ability. However, the research to support this type of intervention is not clear (Meijer & van den Broek, 2010). It is likely that any tool used to enhance spatial ability will do more for making the learner proficient at the tool itself, than it would at improving the spatial ability of the learner (Lowe, 2004). Therefore, the more practical approach to using complex images would be through better design of the learning materials involving images (Wilson, 2015) and the inclusion of alternative perspectives and pacing controls to help all learners learn at their own speed (Hasler *et al.*, 2007; Stiller, Freitag, Zinnbauer & Freitag, 2009; Wouters *et al.*, 2007). The challenge for educators remains to finding the “sweet spot” or balance between cognitive “overload” and judicious use of images to convey the desired content.

Statements on open data, ethics and conflict of interest

Anonymized data sets from this experiment can be retrieved through a request to the corresponding author (TDW). All data collected during the experiments were done so after review and accordance of the institution’s ethical review board responsible for human research. The authors acknowledge that there are no conflicts of interest.

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