

Students' integration of textbook representations into their understanding of photomicrographs: epistemic network analysis

Abstract

Background

Photomicrographs are major biological representations which help students understand more about the structures of cells and tissues. Owing to their abstract nature, students often rely on representations in textbooks to develop their understanding of photomicrographs.

Purpose

This study investigated how students with low, medium and high competence for visualizing photomicrographs integrated textbook representations into their understanding of photomicrographs.

Sample

Twelve, 14-15 year-old students who were studying biology in a UK secondary school participated in this study.

Design and methods

We carried out semi-structured interviews with these students. The modified model of integration of text and picture from Schnotz and Bannert (2003) was used to interpret students' verbal response and their drawing. An innovative discourse analysis approach, Epistemic Network Analysis, was used to analyse the connections between codes which were informed by the model.

Results

Compared to students with high competence, students with low and medium levels of competence did not necessarily understand the structure-behaviour-function relationship of the textual representation, or notice the visual elements in the diagrams. Hence, they could not transfer their understanding of textbook representations into that of the photomicrograph.

Conclusion

This study suggests that the modified model of integration of text and picture can potentially reveal how students with different levels of visualization competence access information from textual and pictorial information. Equally importantly, the study argues for using epistemic network analysis as a tool to examine how students integrate textbook representations.

Keywords

Multiple representations; Photomicrographs; Textbook studies; Visualization competence

Introduction

Photomicrographs play an important role in facilitating students to learn cell biology (Dinolfo, Heifferon, and Temesvari 2007). They are representations which show the features of individual cells, how cells bind together to form tissues, and how tissues are arranged to form larger biological structures. To make sense of photomicrographs, students need to engage at the *submicro* level (molecules), the *micro* level (organelles and cells) and the *macro* level (biological structures), understanding the interrelationships between all three (Tsui and Treagust 2013). However, interpreting photomicrographs is much more difficult than interpreting scientific texts or drawings, because photomicrographs convey real-time representations of cell structures (Postigo and López-Manjón 2012), which provides limited room for re-representation and simplification for students to understand.

Owing to the abstract nature of photomicrographs, students may depend on other, less abstract representations, such as diagrams and texts in textbooks, to interpret the photomicrographs. Past research studies have demonstrated the synergistic effects of diagrams and texts in enhancing students' understanding of biological phenomena (Ainsworth and Loizou 2003; Butcher, 2006; Leivas Pozzer and Roth, 2003). However, students may embark upon different pathways and strategies to integrate diagrams and texts (Cheng and Gilbert 2013; Cheng and Gilbert 2015; Won, Yoon, and Treagust 2014; Pun and Cheung 2021). For example, Cheng and Gilbert (2015) reported that low-achieving students relied on verbal recall of texts in textbooks, instead of creating mental imagery of the visual representations of the human circulatory system.

Textbook representations such as models (Won et al. 2014), biological diagrams (Cheng and Gilbert 2015) and photos (Leivas Pozzer and Roth 2003) often provide ample opportunities for students to engage with complex biological knowledge. Pozzer-Ardenghi and Roth (2005) reported that students learnt more about the morphology of a plant species if they are given a photo showing it together with textual descriptions. However, although most research efforts in the past have been devoted to the content analysis of textbook representations (Postigo and López-Manjón 2018; Vojř and Rusek 2019), only a few research studies investigated how students integrate such representations. These limited research studies often involved students' interpretation of a few selected images from textbooks (see the study by Savasci-Acikalın (2019)), instead of asking them to engage with such representations more holistically, alongside any accompanying text.

Hence, this study is more interested in analysing how students integrate different modes of textbook representation (including text, diagrams etc.) into their understanding of photomicrographs. The study uses the modified model of integration of text and picture from Schnotz and Bannert (2003) to analyse students' integration of textbook representations into their understanding of a photomicrograph of villi. An advanced discourse analysis technique, Epistemic Network Analysis (Shaffer 2017), was used to analyze the interview data. This technique has been used in analyzing science curriculum document and high-stakes assessments (Cheung 2020). Its use in analyzing students' integrating multiple representations is novel in science education.

This study contributes to the literature by (1) characterizing the ways in which students integrate textbook representations into their understanding of photomicrographs; (2) illustrating the potential of the modified model from Schnotz and Bannert (2003) to explore how students integrated textbook representations; (3) arguing for the effectiveness of the use of epistemic network analysis in visualizing students' cognitive pathways.

Literature Review

Multiple Representations in Textbooks

Textbooks are one of the major instructional materials which students use to construct their scientific

knowledge (Cheng and Gilbert 2015; Chiappetta and Fillman 2007; Justi and Gilbert 2002). Although multiple representations, such as texts and pictures, are frequently included in textbooks, different textbook publishers can present a scientific phenomenon in different ways (Devetak, Vogrinc, and Glazar 2010). For example, the diagrams they include may cause students' to build alternative conceptions of scientific phenomena (Catley and Novick, 2008), or the texts which they use may confuse students' understanding of a scientific term (Cho, Kahle, and Nordland 1985). Apart from diagrams and texts, textbooks sometimes may include photographs that illustrate the authentic scientific phenomenon.

However, the intended meaning conveyed by the photographs in textbooks may not be directly accessible to students (Pintó and Ametller 2002; Savasci-Acikalin 2019). Semiotic resources such as texts and diagrams in textbooks may assist students to understand the photograph situated next to these semiotic resources (Dinolfo et al. 2007; Pozzer-Ardenghi and Roth 2005). For example, diagrams may contain visual elements, including colours, graphical elements, sectional drawing and shape that would facilitate students in deepening their understanding of biological phenomena (Postigo and López-Manjón 2018).

Integrating Multiple Representations in Science Education

Past research has drawn on cognitive science to analyze students' integration of multiple representations in science. In the study of Ainsworth and Loizou (2003), twenty students were first allocated to two experimental groups to learn the human circulatory system; one group were presented with texts and another group were presented with diagrams. Afterwards, they were prompted to explain scientific knowledge related to the human circulatory system. Students given the diagrams performed better than those given texts, but there is evidence that both texts and diagrams can improve students' ability to explain scientific concepts. Butcher (2006) conducted a similar study on three groups of students, learning with different kinds of representations related to the human circulatory system: (1) text only; (2) text with simplified diagrams highlighting crucial structural relations; (3) text with more detailed diagrams that resemble the authentic structure. In his study, learners generated inference and reduced comprehension errors if they learnt from simplified diagrams, while they were unable to interpret the structural complexity of the detailed diagrams.

Cheng and Gilbert (2015) investigated students' integration of selected textbook diagrams related to the human circulatory system. They reported that a student could not draw the blood flow in the circulatory system although his verbal recall of the blood flow behavior seemed scientific. Similarly, Won et al. (2014), investigated how students learnt the human breathing mechanism from a textbook diagram and a bell-jar model. They drew on the functional taxonomy of Ainsworth (1999) to analyse students' responses. It was found that students could compare and evaluate two representations when they were aligned together.

Although these studies provide evidence of how students utilise scientific representations, it is important to understand in more depth how students analyse and extract elements from verbal and visual representations and organize them into their mental model of a scientific phenomenon.

Integrating Multiple Representations in Textbooks to Understand Photomicrographs

A photomicrograph cannot be understood if it is not coupled with other representations that explain the photomicrograph (Reid 1990a, 1990b). When a student comes across a new photomicrograph, they will search for a relevant textbook section. In a textbook section (see *Figure 1*), there are two types of textbook representations available to them, *texts* and *diagrams*:

- *texts* include texts above and below the diagram, labels and captions;
- *diagrams* represent the structures visible in the photomicrograph

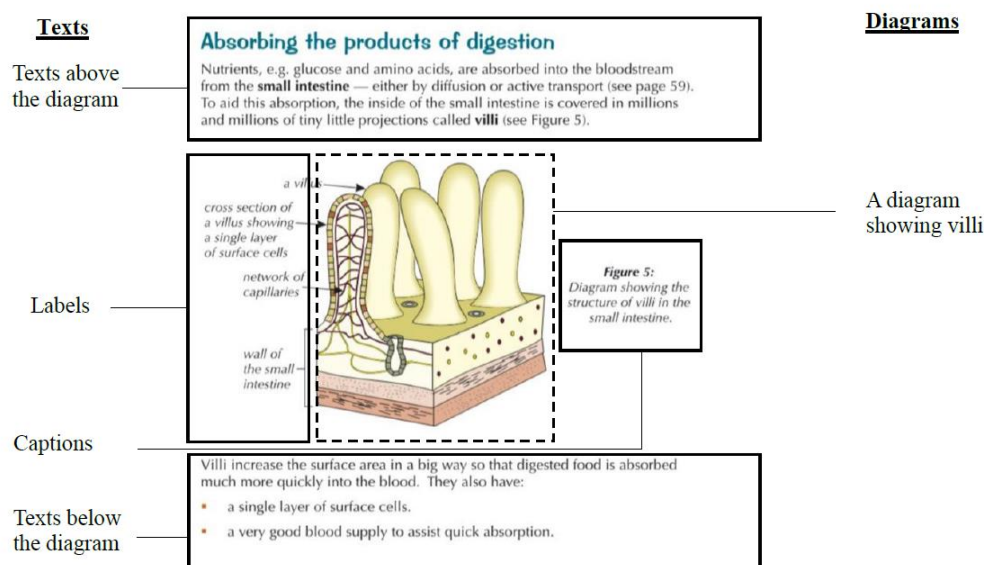


Fig. 1 A typical textbook section that aims to facilitate understanding of villi © **Coordination Group Publications Ltd. (CGP) 2016**

Building on the dual-coding theory of Paivio (2013), Schnotz and Bannert (2003) provided a model that describes the integration of text and picture. As shown in *Figure 2*, unlike dual-coding theory, both visual and verbal information are not immediately encoded in the visual system and the verbal system respectively. They are processed in two pathways which involve analysis of the information: the *textual-processing pathway* and the *perceptual-processing pathway*. In the *textual-processing pathway*, a text is encoded in mental representation of text surface structure, and then propositional representation is generated after semantic processing of that mental representation. A propositional representation specifies the way in which two objects or events are linked together to form a coherent meaning (Mitchell, De Houwer, and Lovibond 2009). For example, the objects, “small intestine” and “digestion” can be linked together to form a propositional representation: “the small intestine is responsible for digestion”. In the *perceptual-processing pathway*, a picture or a diagram is perceived as a mental visual representation. After thematic selection of relevant features of the mental visual representation, a mental model is created. A mental model is a personal and private representation constructed by an individual (Gilbert 2004), which has undergone extraction of external visual and verbal information as well as restructuring (Schnotz & Bannert, 2003). An individual’s mental model is difficult for others to access, and can only be accessed in the form of an *expressed model* (Gilbert 2004).

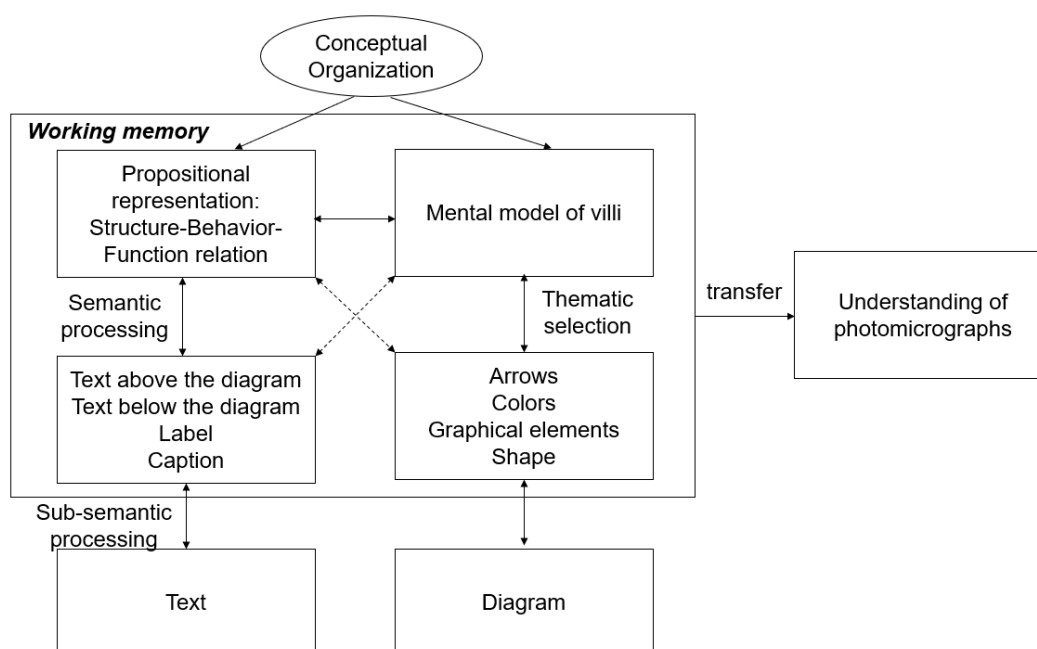


Fig. 2 Modified model of integration of texts and picture (modified from Schnotz and Bannert (2003))

The model from Schnotz and Bannert (2003) is more comprehensive than simple dual-coding theory because it can explain how a learner analyzes and extracts the important part of the information from other distracting parts (Alesandrini 1981; Alesandrini, Wittrock, and Langstaff 2014). Our innate ability to understand multiple representations is not limited to memorizing a picture, but it encompasses analyzing and organizing the components of the picture. For example, we can figure out which components of the picture are important and organize these fragments of mental images with propositional representation to form our own mental models.

An adapted integrated model of text and picture (Schnotz 2002; Schnotz and Bannert 2003) can potentially reveal how students integrate multiple representations in the textbook to make sense of photomicrographs. According to the model presented in *Figure 2*, after sub-semantic processing of text, students can select a range of text resources such as texts above the diagram, text below the diagram, labels and captions to form text surface representation. The textual representation undergoes semantic processing to form propositional representation: articulation of the interrelations among the features of structure, behavior and function (Chi, De Leeuwa, Chiu, and Lavancher 1994). Relevant visual elements such as colors, shape, graphical elements and sectional drawing (Postigo and López-Manjón 2018) are perceived from the picture to form a visual image and thus a mental model of villi. After processing the pictorial and textual information, the working memory will undergo conceptual organisation and transfer the understanding of this information to interpret a photomicrograph of villi. This can take place in the form of an *expressed* model shown in students' drawing (Gilbert 2004).

Aims

There have only been a small number of past research studies that investigated how students learnt from photomicrographs. These were focused around the conceptions held by students when examining photomicrographs (Postigo and López-Manjón 2018), how instruction can improve their ability to identify the photomicrographs (Dinolfo et al. 2007), or what skills students possess to utilise photomicrographs (Cheung and Winterbottom under major revisions). Postigo and López-Manjón (2018) reported that, only with specific instruction did students begin to understand that photomicrographs are only the representations of an object, rather than the object itself. They also

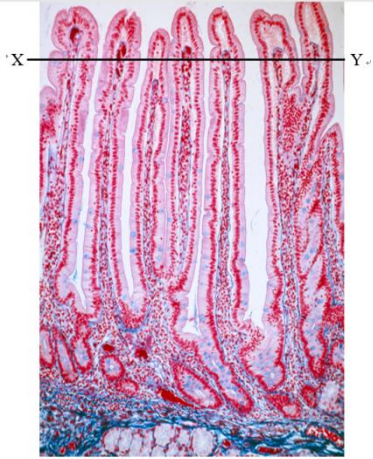
argued the importance of decoding the graphical messages of the photomicrographs autonomously, instead of simply being carried away by the impact, apparent simplicity and immediacy of the image. To autonomously develop their understanding of photomicrographs, students may need to access information from other resources (Dinolfo et al. 2007). As justified previously, textbook representations may offer such resources (Vojř & Rusek 2019). Therefore, drawing on the adapted model of integration of text and picture set out in Figure 2, this study explores how students with different levels of competence for visualizing photomicrographs integrate textbook representations into their understanding of a photomicrograph of villi.

Methodology

Participants and Context

To explore how students integrated textbook representations into their understanding of photomicrographs, we conducted semi-structured interviews with twelve, 14-15 year old volunteer UK students (six males, six females) from a state-funded comprehensive school in the East of England. The school’s performance in public examinations is close to the national average. The school curriculum did not include extensive instruction on the utilisation of photomicrographs or interpretation of textbook representations. Before data collection, teachers’ consent and parents’ consent were sought and participants were informed about the purpose of the study. They previously completed a test which measured their competence in visualizing photomicrographs (see Table 1) (see Cheung and Winterbottom (under major revisions)). Based on the total score, the results of this test classified them into three levels of competence, and four students were selected from the top 25%, the middle 25% (centred around the mean) and the bottom 25% respectively. By comparing the ways in which students with different visualization competence (VC) integrate textbook representations into their understanding of photomicrographs, teachers can make a step forward to help students transfer their understanding of textbook representations to that of photomicrographs.

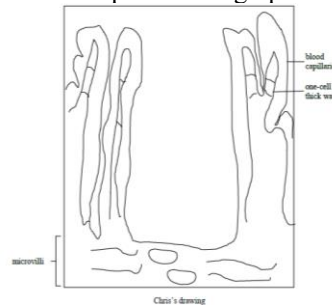
Table 1 The test measuring students’ visualization competence of photomicrographs (Cheung and Winterbottom under major revision)

Components of visualization competence (Chang, 2018; Chang & Tzeng, 2017)	Questions
Interpreting	<div></div> <p>(a) On the photomicrograph above, label all structural adaptations that contribute to the functions of small intestine. In your labels, explain how these adaptations can facilitate the processes and functions of absorption.</p>
Constructing	<p>(b) Draw a biological diagram representing the longitudinal cross-section of part of the wall of the small intestine as shown above. Label all structures in your diagram.</p>
Transforming	<p>(c) Draw a transverse cross-section of villi along the axis of XY as indicated on</p>

the photomicrograph. **Label** all structures in your diagram.

(d) Chris made the following drawing. **Evaluate** on whether his drawing (with labels) adequately represents the longitudinal cross-section of part of the wall of the small intestine as shown in the photomicrograph.

Critiquing



I think Chris's drawing is (adequate/inadequate) in representing the photomicrograph, because...

Semi-structured Interviews

The goal of this interview is to explore students' use of textbook representations to understand photomicrographs, such as texts and diagrams in textbooks. In the *first* phase, students were asked to explicate their understanding of the photomicrograph of villi (see *Figure 3*) without any curricular support. In the *second* phase, they were given a textbook section related to absorption and villi. Students had two to three minutes to familiarize themselves with the textbook section. Afterwards, they were asked to verbalize their understanding of the photomicrograph of villi again, the specific representations of the textbook section they depended on to interpret the photomicrograph, and how they understood these representations. This aligns with the model from Schnotz and Bannert (2003) in which students may form a propositional representation after processing a text-only representation and form a mental model after processing pictorial information. In the *final* phase, students were asked to construct a biological diagram of the structures shown in the photomicrograph. As justified in previous literature, a student's mental model cannot be easily accessed (Gilbert 2004), so this phase of interview can only explore how they transfer their mental model to their understanding of the photomicrograph.

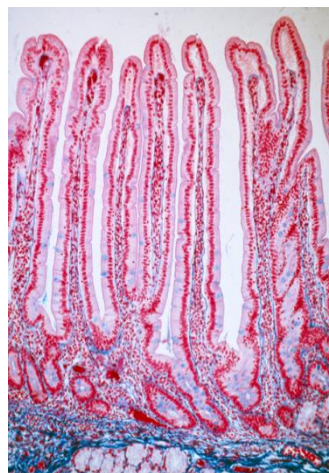


Fig. 3 The photomicrograph used during the interview

In order to choose an appropriate textbook section, over 10 sections connected to the structure of villi were examined from local and international textbooks. This textbook section (see *Figure 1*) was chosen for three reasons: (1) the section contains text and a diagram which aligns with the conceptual

framework in Figure 2; (2) the text and the diagram are in distinctive positions and it is easy to trace the part which students focus on during the interview; (3) the textbook section is for use in the curriculum adopted by the school attended by the participating students. As reported by the participating teacher, the textbook section chosen had not been included in instruction before.

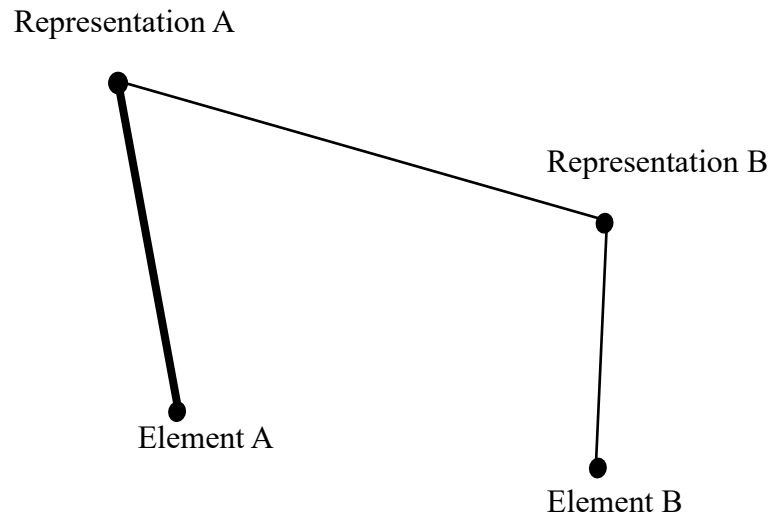
Each interview lasted for around 20 to 35 minutes. During the interviews, a camera was set up directly above the bench where the interviews would be conducted (Cheng and Gilbert 2013). The camera captured students' fingers pointing at the textbook representations and their drawings. Multimodal transcription was carried out on interview videos, including both verbal transcript and corresponding screen shots. Using these transcripts, it was possible to establish how the movement of their fingers corroborated what they said about utilising textbook representations.

Epistemic Network Analysis

Epistemic network analysis (ENA) is used to model the cognitive networks that characterise the association between elements in complex thinking (Shaffer, Collier, and Ruis 2016). This technique has been useful in showing the connections among codes in science education policy document analysis (Cheung 2020), but its use in analysing students' cognitive processing pathway is novel. As the association between visual processing and textual processing is complex in nature, it is argued that the use of ENA can capture the connections of elements during students' integration of textbook representations. Before carrying out ENA, interview transcripts were segmented by idea units and more than one code can be assigned to each idea unit from a student. The codes were then entered into ENA software (<http://www.epistemicnetwork.org/>), which can visualize the presence and the frequency of codes (Shaffer 2017) when students tried to utilise elements in visual and textual representations in textbooks.

The example of what representation and what elements of the representation were utilised by students helps illustrate how to interpret the network of ENA. There are two types of representations: representation A and representation B. There are two elements in both representations, element A and element B. Researchers might want to know how frequently different types of representations, and elements inside the representations, are used by students in the same idea unit. Epistemic networks are useful in visualizing how frequent the connections between codes are. A thicker line of connection shows that the two codes are connected more frequently, while a thinner line of connection shows that the two codes are connected less frequently. According to Figure 4, the frequency of "Representation A" and "Element A" being used together in the same idea unit is the highest, as shown by the thickest line of connections. The connection is more frequent than that between "Representation A" and "Representation B" as well as that between "Representation B" and "Element B".

Figure 4. Epistemic network of different representations and different elements of representations used by students



The elements in the model of integration of texts and pictures from Schnotz and Bannert (2003) form the codes for analysis. Table 2 shows the codes of the textual-processing pathway, while Table 3 shows the codes of the pictorial-processing pathway. These codes were deductively devised from the literature (Postigo and López-Manjón 2018; Schnotz and Bannert 2003). ENA was employed using the codes in Table 2 and Table 3. Table 4 also shows some codes that are inductively developed from students' responses, which indicate to what extent students could transfer (a) their mental model of the villi learnt from the textbook representations, to (b) their mental model involved in visualizing the photomicrograph of villi. Exactly 25% of the interview data were coded separately by the first author and another researcher with college teaching experience, before the first author continue to code the remainder of the data. We discussed the criteria and the evidence we looked for when we applied the codes, with the aim being to ensure that codes contributed to a realistic and consistent interpretation of the data. After finishing coding, the other researcher checked through the application of codes to ensure they were applied appropriately.

Table 2 Codes of the textual-processing pathway

Categories	Description of Codes	Codes
Text-surface representation	Interpret the caption that refers to the representational character of the diagram showing the structure of villi/the 3D structure of villi	Captions
	Interpret the labels in the diagram of villi	Labels
	Interpret the text above the diagram	Text above the diagram
	Interpret the text below the diagram	Text below the diagram
Prepositional Representation	Relate three features (i.e. structure, behavior and function) together to build up a verbal model of the text.	S-B-F relation

Table 3 Codes of the pictorial-processing pathway

Categories	Description of Codes	Codes
Visual perception	Interpret the diagram in general	Diagram
	Interpret elements related to the shape of villi/cells	Shape
	Interpret the visual highlight of relevant information to attract and direction attention	Colours
	Interpret the lines/dots that highlight the features	Graphical elements

Articulate that relevant internal elements are not visible from other perspectives at the same time showing the outside of the rest of the phenomenon (cross sections, longitudinal sections)	Sectional drawing
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Table 4 Codes of transfer of mental model

Categories	Description of Codes	Codes
Transfer of mental model	Drawing shows some evidence of finger-like projections but it does not resemble the shape and the number of villi in the photomicrograph	Limited transfer
	Drawing resembles the shape and the number of villi in the photomicrograph <i>without</i> indication of internal structures	Some degree of transfer
	Drawing resembles the shape of villi shown in the photomicrograph <i>with</i> the indication of internal structures	Successful transfer

Figure 5 shows the actual coded file of a student's interview transcript. The prefix "P" represents the pictorial-processing pathway, while the prefix "T" stands for the textual-processing pathway. We segmented the interview transcript according to the number of turns, while each stanza consists of one turn. This provides micro-analysis of both the multimodal gestures and the verbal representation of students. Afterwards, each idea unit was entered into an excel file. Based on the interpretation of both multimodal data and verbal data, codes in Table 2 and Table 3 were assigned to each idea unit. It should be noted that more than one code can be assigned to a single idea unit. For example, in turn 14, when the student with high visualization competence pointed at the textbook diagram, he said, "I think it's good that it has different tones of *pinky colors* and you can see different *layers*." We just applied the codes "P. Diagram", "P.Colours" and "P.graphical elements" to this idea unit. We then input "1" under the columns corresponding to "P. diagram", "P. colours" and "P. graphical elements" in the excel file. However, the student did not report any structure-behavior-function (SBF) relations in textual representations. Therefore, the codes related to SBF relations were not applied here, as in the turn 14 the student just indicated some processing of the diagrams but limited processing of the text above and below the diagram. As a result, it is considered that there are connections among these three codes. ENA weighs the connections between codes and visualizes these codes in networks. In this paper, we present the networks of groups of students with different VC, so that it facilitates the comparison of how groups of students with different VC integrated texts and pictures into their understanding of photomicrographs.

Figure 5 The actual coded file of a student's interview transcript

Line	Ability	Student Interview Conversation	Code	T.captions	T.labels	T.text abo	T.text bel	T.low-lew	T. SBF re	P
1	High	14 This little bit here. And the diagram.	P.diagram, T.text be	0	0	0	1	0	0	0
2	High	14 I like how little short sentences are put in the bullet points. Just to understand	T.text below the diag	0	0	0	1	1	0	0
3	High	14 Like the single-layer of surface cells... It has a good supply.	T.text below the diag	0	0	0	1	1	0	0
4	High	14 I kind of picture of that and link it to this (point at the photomicrograph).	T.text below the diag	0	0	0	1	1	0	0
5	High	14 Like what this does. How is it good for small intestine. It has a good blood su	T.text below the diag	0	0	0	1	1	0	0
6	High	14 Quickly absorb things.	T.text below the diag	0	0	0	1	1	0	0
7	High	14 It also tells you like... the surface area is big and you can digest food and abs	T.text below the diag	0	0	0	1	0	1	0
8	High	14 I can see like down here it's the wall of small intestine. And then the capillari	P.diagram, P. no ele	0	0	0	0	0	0	0
9	High	14 Like how they cross over in the single-layer of surface cells.	P.diagram, P. no ele	0	0	0	0	0	0	0
10	High	14 Probably the wall of small intestine.	P.diagram, P. no ele	0	0	0	0	0	0	0
11	High	14 It's good the colors there you can more visualize it.	P.diagram, P.colour:	0	0	0	0	0	0	0
12	High	14 Probably the little red bits and dark colors like contrast onto the light.	P.diagram, P.colour:	0	0	0	0	0	0	0
13	High	14 It's kind of pop up more and contrast more.	P.diagram, P.colour:	0	0	0	0	0	0	0
14	High	14 I think it's good that it has different tones of pinky colors and you can see dif	P.diagram, P.colour	0	0	0	0	0	0	0
15	High	14 It is good as you have arrows you know exactly where your read off. Again tl	P.diagram, T.labels,	0	1	0	0	0	0	0

Findings

Figure 6 denotes the epistemic networks of students with different levels of competence for visualizing the photomicrograph of villi. The prefix “P” represents the pictorial-processing pathway while the prefix “T” stands for the textual-processing pathway. A thicker line indicates a more frequent connection between codes, while a thinner line indicates a rarer connection between codes. The size of the dots indicates the frequency of appearance of the codes. As indicated by the biggest dot in the centre, all the three groups of students predominantly depended on the diagrams to interpret the photomicrograph of villi. They also made use of the text above and below the diagram and labels to interpret the photomicrograph.

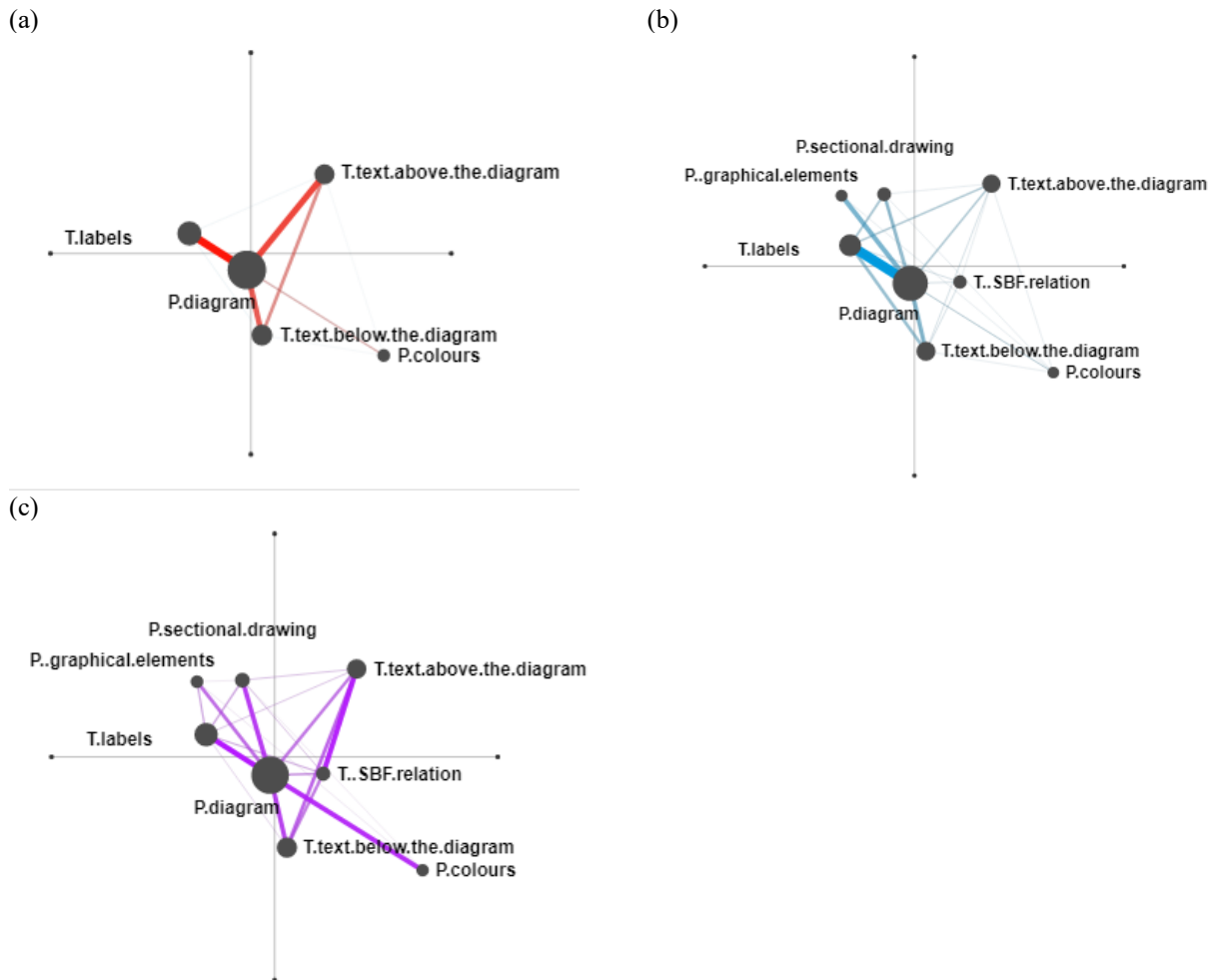


Fig. 6 Epistemic networks of students with (a) low VC, (b) medium VC, (c) high VC (only connected codes are shown)

Table 5 Connection coefficients (CC) of relationships in the epistemic networks.

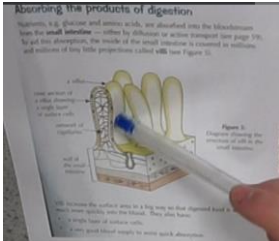
Connections	Levels of competence for visualizing photomicrographs		
	<i>Low</i>	<i>Middle</i>	<i>High</i>
P.diagram-P.colours	0.70	0.50	2.09
P.diagram-P.graphical elements	0.00	2.17	1.43
P.diagram-P.sectional drawing	0.00	1.50	1.95
T.text above the diagram- T.SBF relation	0.00	0.16	2.18

T.text below the diagram- T.SBF relation	0.00	0.33	1.25
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A progression from students with low VC to those with high VC can also be deduced from the networks in Figure 6 (refer to Table 5 for connection coefficients of relationships). As revealed in the network of students with low VC, they reported that they had utilised nearly all representations in the textbook section, they did not mention many visual elements seen in the textbook diagram of villi and did not form a SBF representation when they accessed the textual representations in the textbook section.

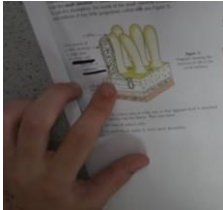
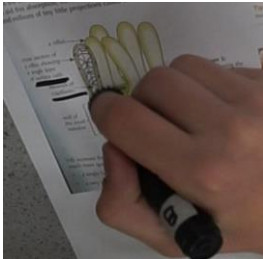
As shown in Table 6, when Student Low-2 was asked about what visual elements helped them to understand the photomicrograph, he did not say that colours, graphical elements, shape or sectional diagram helped him understand the textbook diagram. When he was asked about his understanding of the texts, he just repeated words from the texts, “It’s diffusion. Break down amino acids. And...”. He did not explain how diffusion helps the breakdown of amino acids, and this showed that he did not form a complete SBF representation concerning the mechanism of absorption of food substances across the epithelial cells of villi.

Table 6 Transcript excerpt of Student Low-2

Line	Motion	Verbal response
1		I: So what do you understand about the diagram?
2		S: It just stands out more.
3		I: Anything you understand about the diagram?
4		S: I think it points out what it looks like as well. So just telling you...
5		I: So which particular visual elements help you understand the diagram?
6		S: Just point out what things are... like villus.

The epistemic network of students with medium VC in Figure 6b shows that there were connections between the diagram of villi and visual elements within the diagram, including graphical elements (2.17), the sectional diagram (1.50) and colours (0.50). However, the connections between the textual representations and the SBF relation are still very rare. Table 7 shows the transcript extract from Student Middle-3. She described how she inferred the position of epithelial cells by the separation of squares, as well as inferring the location of blood capillaries by their colours. Although students with medium VC started to utilise the visual-processing pathway, they did not utilise the textual-processing pathway to make sense of the scientific texts presented in the textbook section.

Table 7 Transcript extract from Student Middle-3

Line	Motion	Verbal Response
1		I: How about the visual elements in the diagram?
2		S: I think the visual element also helps. Because with this it helps you understand a lot easier to actually visualize how one-cell thick actually looks. It gives you the ideas of how much capillaries they are in single villi.
3		I: What kinds of visual elements?
4		S: Like the colors and the separation of square (pointing at the epithelial cells) on this. Obviously the network of capillaries and then that sort of help you to attach to the small intestine.

The epistemic network of high VC (Figure 6c) is similar that of medium VC. There are connections between sectional drawing, colours, graphical elements and the diagram of villi. However, the connections between the textual representations and SBF relations in the network of students with high VC (*T.text above the diagram-T.SBF relation*: 2.18; *T.text below the diagram-T.SBF relation*: 1.25) are more frequent than those with medium VC (*T.text above the diagram-T.SBF relation*: 0.16; *T.text below the diagram-T.SBF relation*: 0.33). It shows that students with high VC were more capable of relating the features of structure, behavior and function together to make sense of the textual representations in the textbook section. This is evidenced by the transcript extract from Student High-1 below, who was able to explain how the blood capillaries in the villi facilitate the entire processes of absorption. The propositional representation formed by this student was much more complex than that formed by Student Low-2.

S: So the nutrients come in from there the villi has a big surface area. Or they can kind of uptake and absorb food by active transport and diffusion. And they come through the network of capillaries. They go through the capillaries down here. And then into the wall of small intestine. And there where they did.

To probe into how students transferred their understanding of textbook representations into that of the photomicrograph, they were asked to “draw and label a biological diagram representing the longitudinal cross-section of part of the wall of the small intestine as shown in the photomicrograph”. In this part of the interview, we probed into whether students can gain a basic understanding of the structures of villi in the textbook diagram, build on their understanding and apply these understandings to visualizing the photomicrographs. The aim of this question is to understand how textbooks helped students to interpret the photomicrographs. Table 8 shows the codes assigned to each student and Table 9 shows their biological drawings. From Table 8, three out of four students from both low and medium VC groups exhibited limited transfer, which indicates that their drawing resembles the diagram in the textbook section instead of that in the photomicrograph. For example, as shown in the drawing from Low-1, they drew only four villi, but in fact there were more than seven in the photomicrograph (Figure 3). Some students (i.e. Medium-1 and Medium-2) tried to represent the internal structures inside just one villus instead of all villi, possibly because the textbook diagram only indicated the internal

structures of one villus for illustration purpose, and they directly copied their biological drawing from the textbook diagram instead of the photomicrograph. Moreover, Student Low-3 and High-2 could draw the outline of villi as shown in the photomicrograph but did not draw the internal structures of villi. This contrasts with the three students with high VC who were able to draw the shape and internal structures of villi based on the photomicrograph.

Table 8 Students' performance on transferring their understanding of textbook representations into that of the photomicrograph

VC	Student ID	Limited transfer	Some degree of transfer	Successful transfer
Low	Low-1			
	Low-2			
	Low-3			
	Low-4			
Medium	Medium-1			
	Medium-2			
	Medium-3			
	Medium-4			
High	High-1			
	High-2			
	High-3			
	High-4			

Table 9 Students' biological drawings on the photomicrograph of villi

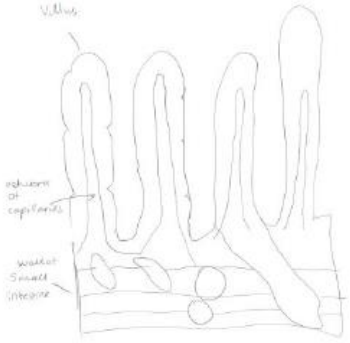
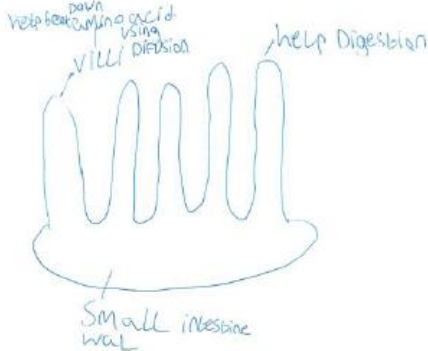
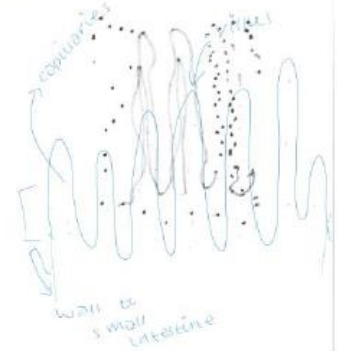
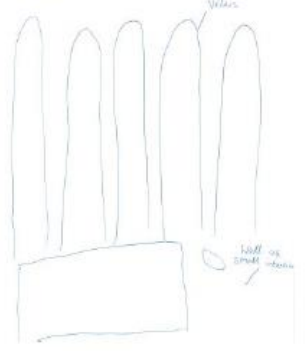
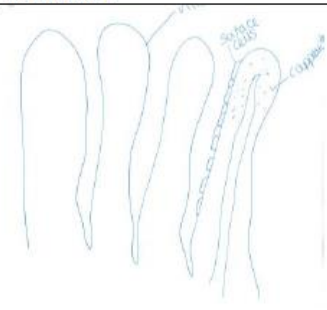

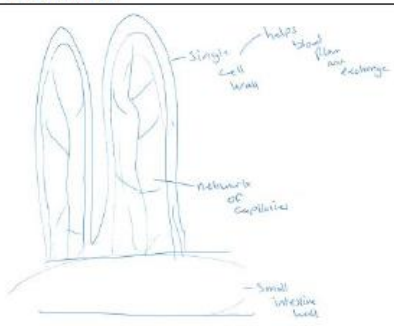
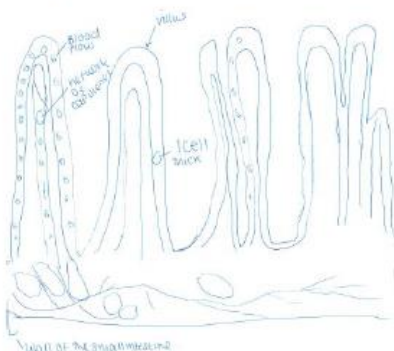
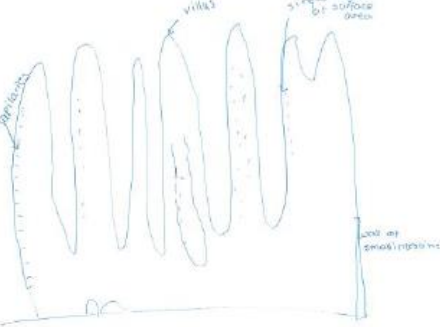
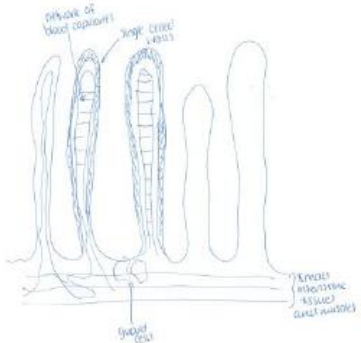
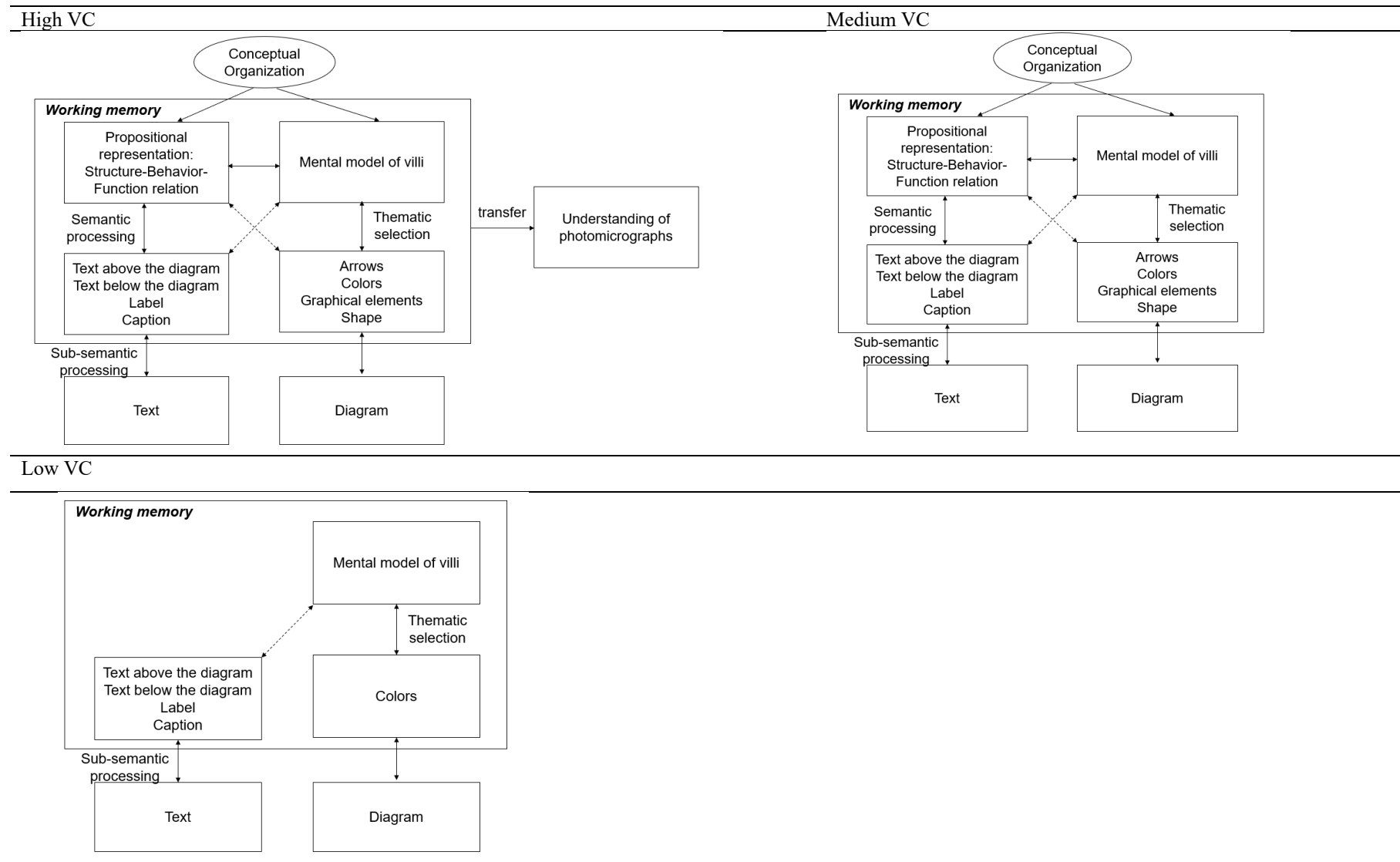
Low-1	Low-2	Low-3	Low-4
			
Medium-1	Medium-2	Medium-3	Medium-4
			
High-1	High-2	High-3	High-4
			

Table 10 The cognitive pathways of students with different VC



Discussion and Implications

This paper reports a study which examines how students with different levels of VC integrated textbook representation into their understanding of photomicrographs. Students with low VC could not form SBF propositional relationships when processing textual information or perceive detailed visual elements in the textbook diagram; therefore, their mental model of villi was directly affected by the superficial processing of textbook representations (see Table 10). Their transfer of understanding of textbook representations to that of the photomicrograph of villi was limited, possibly because they did not process enough textual and visual elements within their working memory (Mayer and Moreno 2003; Schnotz 2002; Schnotz and Bannert 2003). On the other hand, students with medium VC started to perceive visual elements in pictorial representations and form SBF propositional relationships from textual representations. Students with high VC could form SBF propositional relationships and perceive detailed visual elements in the textbook diagram to form a mental model, which could be transferred to the understanding of the photomicrograph of villi. In short, the findings suggest that the superficial processing of textbook representations is associated with students' low competence in visualizing photomicrographs.

[Insert Table 10]

Textbook representations may not necessarily facilitate students to understand photomicrographs due to the complexity and abstractness of photomicrographs (Dinolfo et al. 2007; Eilam 2013; Postigo and López-Manjón 2012). Students with low VC were not able to form a propositional representation when they read texts representing complex scientific knowledge. Students with low VC could only repeat what they had *read* from the texts when they were asked what they *understood* from the texts. In the pictorial-processing pathway, they were also not able to perceive the detailed visual elements in the textbook diagram which could potentially help them understand the photomicrographs. For example, a line of several squares at the periphery of villi in the textbook diagram indicates the location of one-cell thick epithelial cells. Although a lot of researchers believed that one representation can facilitate the understanding of another representation (Ainsworth 2006; Ainsworth and Loizou 2003; Tsui and Treagust 2013), sometimes it depends on the quality of representations as well as the skills students have acquired to utilise and integrate multiple representations in textbooks. As a result, science educators should not always assume that designing high quality textbook representations can enhance student's understanding of scientific phenomena, but they should note that the skills in utilising and integrating these representations vary among students.

The results of this study extend the work on multiple representations in science education by illustrating the potential of studying students' cognitive pathways of integrating textual and pictorial representations. Previous studies in this area focused on the skills that students utilise to translate across representations (Chang 2018; Kozma and Russell 2005), and that students utilise to interpret photomicrographs (Dinolfo et al. 2007; Postigo and López-Manjón 2012). However, few have considered the use of a fine-grained information processing model to explore how students extract elements from textual and pictorial representations. More importantly, none of these studies examined how students transfer their understanding of a textbook section to that of photomicrographs. The modified model of text and picture from Schnotz and Bannert (2003), coupled with the epistemic network analysis, paved a way for researchers to understand how students associated elements in textbook representations. Epistemic network analysis helps visualize the extent of connections of elements in textbook representations. More importantly, the networks of students with different visualization competence can be compared. Understanding this variability is crucial for science educators to design curriculum materials that differentiate for students with different visualization competence.

One of the limitations is that although students retrospectively reported they utilise specific elements within textbook representations, it does not mean that they utilised cognitive pathways to probe into these elements. This limitation can be counterbalanced by two measures. Firstly, multimodal recording can triangulate what they verbally reported and which visual elements they were pointing at (Cheng and Gilbert 2013; Cheng and Gilbert 2015). Secondly, when we analyze the interview transcripts, the codes were applied only if the student gave some specific examples of how these visual or textual elements helped them construct their understanding of the photomicrograph of villi. Given the scarce number of studies that examine how students utilise textbook representations to understand photomicrographs, this study makes contributions in this regard by capturing the detailed process through which students understand the elements in representations. It is suggested that future research can make use of eye-tracking techniques to explore the reading paths of students when they encounter textbook representations and photomicrographs.

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