

## Exploring students' visualization competence with photomicrographs of villi

Photomicrographs are representations of small-scale entities. It has been long argued that students can be weak in perceiving microscopic entities compared to macroscopic entities. However, only a small body of research has investigated how students utilise photomicrographs to make sense of biological phenomena. This study uses a theoretical construct, “visualization competence”, to explore students' skills and practices in utilising photomicrographs. Fifty UK students' visualization competence with photomicrographs of villi were measured by open-ended questionnaires. Content analysis showed a wide range of students' performance in all components of visualization competence with photomicrographs, namely constructing, interpreting, transforming and critiquing. Students' performance on sub-components within each skill component of visualization competence for the photomicrograph of villi were also analysed. The mean scores of constructing a biological diagram resembling the photomicrograph and critiquing whether a representation resembles the photomicrograph were higher than that of interpreting the photomicrograph. Transforming the longitudinal section of photomicrographs into the transverse section had the lowest score among all four skill components. Moreover, the sub-components which rely heavily on textual processing were found to be significantly correlated with each other. Implications for teaching and learning of photomicrographs were discussed.

**Keywords:** photomicrographs; multiple representations; visualization competence; biological representations

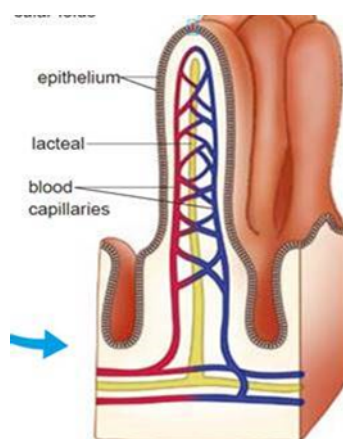
### Introduction

Photomicrographs are biological representations that convey the structures of cells and tissues. They show the spatial location of cells and how cells are arranged to form a tissue. Students should learn how to comprehend photomicrographs if they want to gain a deeper understanding of biological phenomena (Dinolfo, Heifferon, & Temesvari, 2007; Kiely, 1958). Recent research studies have revealed students' skills in utilising multiple representations in science education. For example, Stieff and DeSutter (2020) studied how students drew particle models of solutions with the same concentration but different volumes; Sit (2020) investigated how students interpreted diagrams on the topic of cell division. However, these findings may not be directly transferred to understanding students' skills in utilising photomicrographs.

Photomicrographs contain more detailed information and are more abstract than textbook sectional diagrams given that they convey microscopic cells and tissues at one particular instance in time (Eilam, 2013). The way of staining, biopsy and preparation of slides will affect the production of photomicrographs (Mikula & Lennox, 1979). In common textbook diagrams of villi (see Figure 1), the blood vessels are located in the centre of villi, with blue colour denoting deoxygenated blood and red colour denoting oxygenated blood. By using these conventions, students can identify the location of blood capillaries easily and relate it to the function of blood capillaries in relation to nutrient absorption. The edge of the villi presented in the textbook diagram is smooth and it is easy to identify each of the villi. However, in photomicrographs, the edge of villi is not completely smooth. Blood capillaries are not easily seen in the photomicrographs of villi as the colour of stain will affect the identification of blood capillaries. To identify the structures in photomicrographs, there is a need for students to depend on representations with clear conventions, such as textbook diagrams to

visualize photomicrographs (Cheung and Winterbottom, 2021). In sum, photomicrographs are defined as abstract representations because students' understanding thereof depends upon experience with perceptually rich, concrete representations, such as textbook diagrams and 3D models (Cheung and Winterbottom, 2021; Goldstone & Sakamoto, 2003).

Figure 1. An example of a textbook diagram of villi (Chan et al., 2015)



In light of the above, the present study uses a theoretical construct from Chang and Tzeng (2017) - “visualization competence” - to explore how students visualize a photomicrograph of villi (a structure present in the mammalian small intestine which facilitates food absorption). Visualization competence describes the skills and practices of utilising representations in science. In this study, it delineates four major components of competence in utilising photomicrographs: constructing, interpreting, transforming and critiquing.

The purposes of this study are to (1) explore students' strengths and weaknesses in terms of different components or sub-components of visualization competence for photomicrographs and (2) examine the correlations among these components or sub-components. Fifty British students were invited to complete an open-ended questionnaire on their visualization competence for photomicrographs of villi. In this study, we focus on how students utilise photomicrographs after formal instruction, as research studies reveal that students do not acquire competence for utilising photomicrographs without formal instruction (Dinolfo et al., 2007). Their competence in utilising photomicrographs will only be developed after formal instruction or reading other textbook representations (Cheung and Winterbottom, 2021). By identifying the components that students are weak in, researchers can develop strategies to improve students' visualization competence for photomicrographs. After identifying correlations among components or sub-components of visualization competence, researchers can understand what components should be taught together and what components should be taught separately.

## Literature Review

### *Making sense of photomicrographs*

Photomicrographs, which are one of the major biological representations, have received relatively little attention in the science education literature. Compared to photographs, photomicrographs are more abstract, as the approach to staining, the biopsy method and the organism involved may yield different images of the same type of cell. Recognition and interpretation of tissue organization requires exposure to diverse images (Hirt, Leonard and Lee, 2020). For example, when

students view different photomicrographs of villi, they would realize that the blood capillaries are not neatly arranged in the centre of villi. In the photomicrographs of villi, oxygenated blood and deoxygenated blood will not be indicated clearly by red and blue colours respectively. The colour of blood capillaries depends on the stain used by the histologists. Therefore, it is necessary for students to develop skills to recognise the patterns in photomicrographs (Hirt, Leonard and Lee, 2020). However, photomicrographs are considered important to teaching and learning. Students can learn about causes of disease by looking at the abnormality shown in photomicrographs; for example, inflammation of the digestive tract can be characterised by the loss of integrity of epithelial cells (the outer layer cells of the small intestine). Incorporating photomicrographs into teaching and learning of cell structures can enrich students' understanding of such structures and their intrinsic motivation to learn the microscopic structure of tissues (Mikula & Lennox, 1979). Given such evidence of the importance of photomicrographs in biology education, it is important to understand the ways in which students may comprehend photomicrographs.

Although photomicrographs have different properties to photographs, they both capture abundant information that can encourage active learning of biology (Krauss, Salame, & Goodwyn, 2010). Students often find that information in photographs is more interesting than texts in a biology textbook (Postigo & López-Manjón, 2018; Pozzer-Ardenghi & Roth, 2005). Importantly, Pozzer-Ardenghi and Roth (2005) suggested that the photographs in textbooks can serve decorative or complimentary functions. Decorative photographs do not add extra information to texts, while complementary photographs provide additional information that cannot be represented by the texts. Complementary photographs, therefore, may have more pedagogical value than decorative photographs (Slykhuis, Wiebe, & Annetta, 2005). It is argued that photomicrographs are often complementary, as they convey a lot of information that is difficult to represent through text. For instance, villi are described as finger-like projections in the texts in textbooks. But in fact, the photomicrograph of villi shows that the villi in the human body are not perfectly finger-shaped and the shape of each of the villi is different.

To access the complementary information in photomicrographs, not only do students process the explicit information in photomicrographs, but they also need to process its conceptual information (Postigo & Pozo, 2004). For example, for students to understand components shown in the photomicrograph of villi, they have to understand three features: structure (what it is) (denoted as S), behaviour (what it does) (denoted as B) and function (what purpose it serves) (denoted as F) (Chi, De Leeuwa, Chiu, & Lavancher, 1994). The following exemplifies the use of such features to think about the one-cell-thick epithelial cells on the surface of the villi:

- *Structure* (S): one-cell-thick epithelial cells
- *Behaviour* (B): digested food substances such as amino acids and glucose pass through this layer of cells and enter blood capillaries
- *Function* (F): minimizes the distance of diffusion of absorbed substances

The features of each component are interrelated to one another (Cheng & Gilbert, 2015). As shown in the above example, the epithelial cells are one-cell thick (S) so digested food substances such as amino acids and glucose can pass through and enter blood capillaries (B), minimizing the diffusion distance for absorbed food substances (F). The interpretation of a component shown in the photomicrograph often requires students to relate one feature to another feature, so that students' learning from photomicrographs can be maximised. In this example, if students want to make sense of the one-cell-thick-epithelium feature of villi, they have to know how food is transported from the lumen of the small intestine into the blood capillaries across the epithelium, such that thin epithelium can shorten the distance of diffusion.

### *Visualization competence for photomicrographs*

Past research has used a number of theoretical constructs to explore students' competence in utilising multiple representations. Examples of these include representational competence (Halverson & Friedrichsen, 2013; Kozma & Russell, 2005), meta-representational competence (diSessa, 2004; diSessa & Sherin, 2000), representational fluency (Moore, Chamberlain, Parson, & Perkins, 2014; Warfa, Roehrig, Schneider, & Nyachwaya, 2014), visual literacy (Ametller and Pintó, 2002; Schönborn and Anderson, 2010), as well as visualization competence (Chang & Tzeng, 2017). Although they share some similarities, the theoretical construct "visualization competence" suits the present study, as outlined below.

Representational competence describes the skills that students need to utilise representations to discuss and understand scientific processes and entities (Kozma & Russell, 2005). Kozma and Russell (2005) contend that representational competence can be classified into different levels: at the bottom level, students can generate representations based on the observable features of the phenomenon; at the top level, students can utilise specific features of the representation to explain scientific phenomena and warrant claims within social contexts. By contrast, meta-representational competence describes the native ability that students hold to generate, choose, utilise and create representations (diSessa, 2004; diSessa & Sherin, 2000). From this perspective, researchers should be concerned with how students develop their competence in utilising multiple representations through both social activities and formal instruction (diSessa, 2004). In other words, students' experiences which take place outside normal schooling should be included when considering their ability to utilise multiple representations. However, students can only learn how to read different photomicrographs with the guidance of the science teachers. They are more knowledgeable in helping students identify the biological features in photomicrographs. Hirt, Leonard and Lee (2020) reported that after students received feed forward training, they began to recognize simple tissues in photomicrographs; Postigo and López-Manjón reported that after students received explicit instruction, they began to understand that photomicrographs are not merely copies of realities. The findings showed that students cannot develop their capacity to understand photomicrographs if they do not receive explicit instruction on how to interpret the photomicrographs of different biological structures.

Another potential construct, visual literacy, has been used to explore students' skills in utilising multiple representations. Visual literacy is defined as the ability to read, write or draw external representations (Ametller and Pintó, 2002). Experts with visual literacy should have the ability to "(1) decode the symbolic language composing an external representation (ER); (2) evaluate the power, limitations and quality of an ER; (3) interpret and use an ER to solve a problem; (4) spatially manipulate an ER to interpret and explain a concept; (5) construct an ER to explain a concept; (6) translate horizontally across multiple ERs of a concept; (7) translate vertically between ERs that depict various levels of organization and complexity; (8) visualize orders of magnitude, relative size and scale." (Schönborn and Anderson, 2010, p. 349). This construct focuses on both vertical and horizontal translation across multiple representations: vertical translation refers to the move between multiple representations of various levels of organization and complexity; horizontal translation refers to the move between multiple representations of the same system at the same level of organization (Linenberger and Holme, 2015). Although this construct takes vertical translation and horizontal translation between biological representations into account, the numerous cognitive skills required are not developmentally appropriate to secondary school students. Therefore, there is a need for this study to adopt a construct with organized, central components which are developmentally appropriate to secondary biology education.

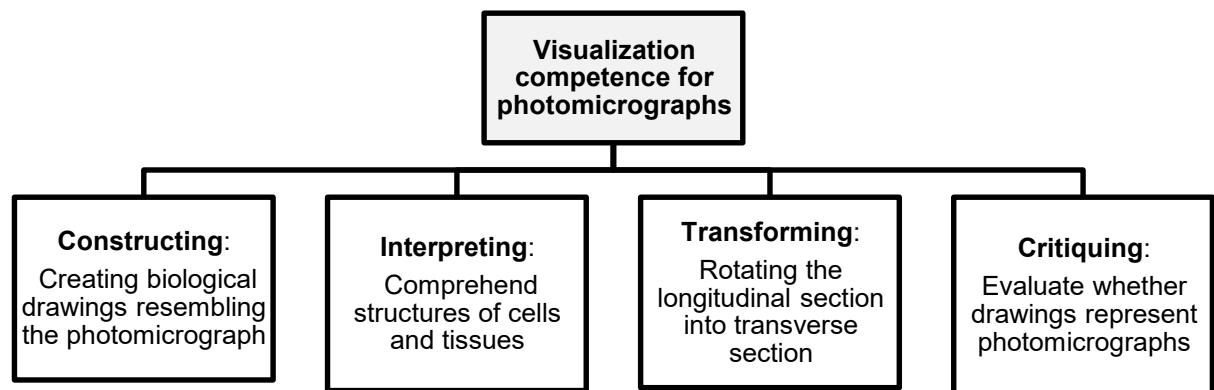
In this study, “visualization competence” (Chang and Tzeng, 2017) is chosen to explore students’ skills and ability to utilise photomicrographs. According to Chang and Tzeng (2017), “visualization competence” comprises four major components: *constructing*, *interpreting*, *transforming* and *critiquing*. The basis of creating this construct is the importance of “visualization” in science education (Gilbert (2005). “Visualization” describes how students generate and externalise mental imagery of a scientific phenomenon (Gilbert, 2005, 2008). It is commensurate with the aim of the present study; that is, studying how students generate mental images to externalise a photomicrograph of villi. Although “visualization competence” is a subset of “representational competence” (Chang & Tzeng, 2017), its components should be considered as four individual components, instead of four successive components. Kozma and Russell (2005), in their five levels of representational competence, assumed that critiquing is at the most advanced level while constructing is at the most basic level, but such an assumption was not empirically warranted.

As a result, without substantial empirical evidence, this study considers the four components of visualization competence as sharing equal importance. In the study of Chang and Tzeng (2017, p.1210-1211), which focused on how students used multiple representations to explain matter at particulate level, they defined the four components in the following ways:

- (1) *constructing*: creating a series of external multiple representations such as graphs, tables and diagrams to describe science concepts and phenomena;
- (2) *interpreting*: inferring the meaning of external visualizations by using science concepts;
- (3) *transforming*: generating new external visualization to substitute or supplement the original visualization;
- (4) *critiquing*: evaluating whether an external visualization has achieved certain criteria.

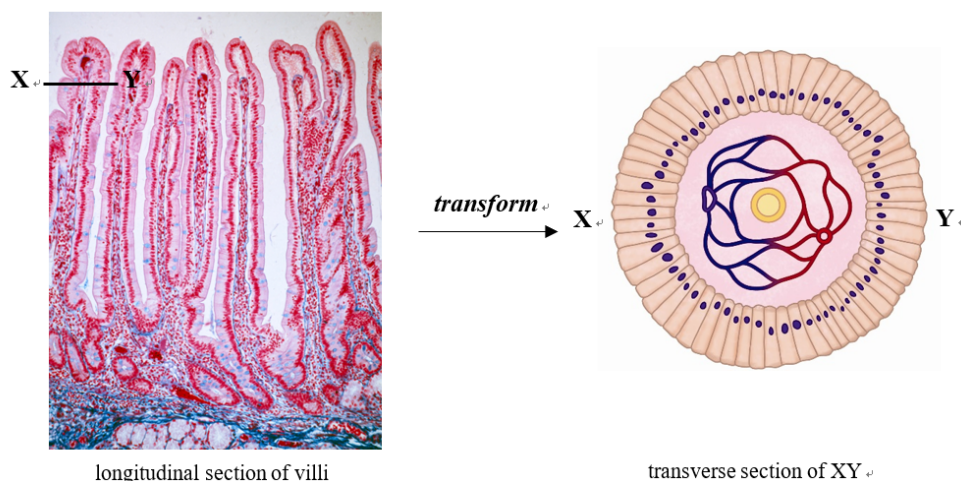
Chang (2018) applied the two components “constructing” and “transforming” to the examination of how students utilised animations on the topics of carbon cycling and state of matter. She further differentiated the components of “constructing” and “transforming” into four finer aspects: use of dynamic representations, use of multiple representations, use of adequate science concepts and use of visualization strategies. This delineation of the four components of visualization competence (Chang and Tzeng (2017) was intended to apply to how students utilise different kinds of scientific representations, rather than one specific kind of representation. Although these four aspects are not applicable to the current aim of this study, it shows that these components could be operationalized such that finer sub-components can be developed from students’ performance in utilising photomicrographs. Owing to the above, the four components of visualization competence are adapted for the present study as follows (see Figure 2):

Figure 2. Four components of visualization competence for photomicrographs



- (1) *constructing*: creating biological drawings that depict the structures represented (referents) in the photomicrographs;
- (2) *interpreting*: comprehending the structures of tissues and cells (i.e. blood capillaries, epithelial cells) and relating their structural features to the behavioural and functional features;
- (3) *transforming*: generating a new external visualization from an axis indicated in the photomicrograph, e.g. transforming a longitudinal section of a villus into a diagram of a transverse section of a villus (see Figure 3);
- (4) *critiquing*: evaluating whether drawings from other sources can accurately represent the referents shown in the photomicrograph of villi.

Figure 3. Transforming an axis of a photomicrograph showing a longitudinal section of a villus into a diagram of a transverse section of a villus (The right diagram adapted from Chan, Fung, Li, and Ng (2015))



To communicate the observations shown in photomicrographs, scientists need to draw biological diagrams according to the photomicrographs. This helps them to communicate with peers and understand the structures of cells and tissues in detail (Kiely, 1958); therefore, *constructing* biological drawings on the photomicrographs is an important skill.

As justified previously, it is more meaningful for students to relate the structural features to the behavioural and functional features instead of just identifying the structural feature (Chi et al., 1994); therefore, interpreting the structures of tissues and cells (i.e. blood capillaries, epithelial cells) shown in photomicrographs by relating their structural features to the functional and behavioural features is an essential skill in utilizing photomicrographs. More importantly, a learner who is competent in visualization should learn how to transform across two-dimensional (2D) and three-dimensional (3D) images (Abraham, Varghese, & Tang, 2010). Biology textbooks often included frontal view diagrams to teach biological structures (Carvalho, Silva & Clément, 2007). At the same time, photomicrographs provided to students at secondary school level often represent biological structures as frontal 2D images. However, research studies have shown that representations of a singular perspective cannot facilitate students to understand the spatial location and position of an organ (de Jager, 2017). Therefore, to better understand the position of structures, it is necessary for students to acquire the skill of transforming an axis of the longitudinal section of a villus into a transverse section of a villus. Additionally, some biological diagrams in curriculum materials, such as those in textbooks, may simplify the structures of referents shown in photomicrographs. These drawings often use spatial isomorphism and representational conventions to represent the referents shown. *Spatial isomorphism* refers to the similarity in spatial relationship of the components in a diagram in relation to their referents in a photomicrograph (Cheng & Gilbert, 2015; Hegarty, 2011); *representational conventions* refer to the use of labels to represent the structures. However, textbook diagrams do not always accurately represent scientific phenomena (Stylianidou, 2002). Hence, if students come across a photomicrograph and a sectional diagram at the same time, they should possess the ability to critique whether the structures represented by the sectional drawing can resemble the referents in the photomicrograph; therefore, critiquing whether drawings from other sources can fully represent the referents shown in a photomicrograph is also a crucial skill.

Instead of visualization competence, past research studies focused on studying students' conceptions about, and identification of features within, photomicrographs. Postigo and López-Manjón (2012) found out that most students held a realistic conception that photomicrographs are merely a copy of reality. Similarly, Dinolfo et al. (2007) found that only students with instruction were able to identify the structures in photomicrographs. In fact, utilising photomicrographs is not only limited to conceiving the constructivist nature of photomicrographs or just identifying the structures in the photomicrograph, but instead students should acquire a range of skills to communicate their own snapshotted photomicrographs: *constructing*, *interpreting*, *transforming* and *critiquing*.

## Focus of the study

This study addresses the following questions:

- (1) How do students perform in the four components of visualization competence for a photomicrograph showing villi, namely constructing, interpreting, transforming and critiquing?
- (2) What component(s) of students' visualization competence for a photomicrograph showing villi is/are correlated to each other?

## Methodology

### *Participants and Context*

The sampling strategy used in this study is purposive sampling (Etikan, 2016). Fifty 14-15 year old students (21 males, 29 females) were the target age group of this study because (1) they have substantial experience in looking at photomicrographs in school textbooks, so that their usual ways of understanding photomicrographs can be studied, and (2) they have a basic knowledge of the topic of digestion, so they can understand the photomicrograph of villi. This group of students came from a

rural state-funded secondary school in the UK, and had begun to study for their GCSE course in biology.

According to the science teachers at the school, instruction involved little focus on visualization practices. Textbooks were rarely used, and interpretation of photomicrographs was not an examination requirement. That said, students had started to use photomicrographs in Year 9. In collaboration with the participating teacher, biological representations in the school's teaching materials related to digestion and absorption were identified. This was important to confirm that students have encountered the cross-section of villi as well as the relationships between structure, behaviour and function. For example, the teaching materials designed by the teacher included the idea that villi have a thin wall such that it can shorten the distance of diffusion of glucose and other nutrients. Therefore, the "interpreting" component in our coding rubric considered whether students can link the structural features they observed from the photomicrographs to the behavioural and functional features. Moreover, the questions in such instruments were designed to require students to apply and integrate the content they learnt and to avoid mere replication of any single figure or representation in the teaching materials.

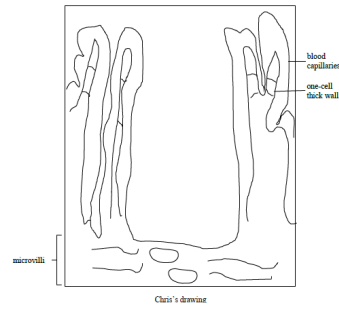
### ***Students' Visualization Competence for Photomicrograph Questionnaire***

The Students' Visualization Competence for Photomicrograph Questionnaire (SVCPQ) consists of one photomicrograph and four items (Table 1). The research team comprises three faculty academics from the field of science education. We set out criteria to choose a photomicrograph of villi: (1) it showed clearly the arrangement of structures of a longitudinal section of villi, which includes the blood capillaries and a single layer of surface cells; (2) the structures (i.e. blood capillaries and wall of villi) shown in the photomicrograph should already be a part of the participating teachers' teaching materials. Over 10 photomicrographs of villi were examined from a range of local and international curriculum materials and one of them (Figure 3) was eventually selected because it showed clearly the structures of a longitudinal section of villi, which includes the blood capillaries and a single layer of surface cells. Two science education academics and the participating teacher reviewed SVCPQ, and it was piloted to eight students.

Table 1. Students' Visualization Competence for Photomicrograph Questionnaire (SVCPQ)

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





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

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Each item explores one component of students' visualization competence (see **Table 1**). The importance of these components (*constructing*, *interpreting*, *transforming* and *critiquing*) was justified in previous research studies (Chang, 2018; Chang & Tzeng, 2017).

- The *constructing* item requires students to generate a biological drawing that represents the referents shown in the photomicrograph of villi;
- the *interpreting* item requires students to comprehend the structures (i.e. blood capillaries) and relate the structural adaptation to the functions, using science concepts;
- the *transforming* item requires students to create a new external visualization to represent the transverse section of an axis of the photomicrograph of villi, such as a longitudinal section of villi;
- the *critiquing* item requires students to evaluate whether others' biological drawings can reflect the referents of the photomicrograph of villi. The critiquing item has a design similar to that from Merritt and Krajeik (2009) and Chang and Tzeng (2017), which puts students into a situation where they evaluate one student's (Chris) drawing.

The drawing in the *critiquing* item (Chris's drawing) shows some deficits in representing the referents of the photomicrograph, such as the mistaken use of conventions and spatial isomorphism. The mistaken use of conventions refers to the inappropriate use of colour, arrows, icons and labels for a diagram to represent its referents; the mistaken spatial isomorphism refers to the inappropriate spatial location of structures in the diagram that resembles the authentic structure (Hegarty, 2011). In Chris's drawing, the labels do not match with the structures, and the spatial location of the diagram does not resemble the referents shown in the photomicrograph of villi.

We drafted the first version of SVCPCQ and sent it to the participating teacher and a PhD student whose expertise is microscopy for review. Afterwards, these instruments were piloted to eight students. We discussed students' responses and adjusted some wording in the questions in the SVCPCQ. The following revisions were made after pilot studies.

- The *constructing* and *transforming* questions did not emphasize the task of labelling biological structures in their drawings, so students seldom put labels in their drawings. Therefore, the action words "draw" and "label" were emboldened.
- Initially, in question (d), students were asked to critique whether two drawings resembled the referents of photomicrographs, but students only focused on contrasting the two drawings. Therefore, the revised version has only one drawing for students to critique.

## Data analysis

Students' performance was analyzed in accordance with four components of visualization competence: *constructing*, *interpreting*, *transforming* and *critiquing*. The coding rubric in *Table 2* is devised deductively and inductively according to past literature (see Chang, Quintana, and Krajcik (2010), Chang (2018) and Chang and Tzeng (2017)) as well as students' responses. The first author and a biology teacher were responsible for forming a coding scheme to code students' responses. They were sensitive to theories on visualization of biological multiple representations, such as spatial isomorphism and use of conventions (Cheng and Gilbert, 2015). This forms the sub-components of *constructing* and *transforming*:

- spatial isomorphism (sub-component 3 and 5) refers to how students' drawing resembles the spatial location of referents shown in the photomicrograph;
- use of conventions (sub-components 4 and 6) refers to the number of labels students gave to biological structures.

Table 2. Rubric for analyzing SVC PQ and the percentage of students falling into each code

Components	Criteria	Score	Description of Levels	Percentage
Interpreting	1. Number of structural adaptations	4	<b>Four</b> structural adaptations are indicated.	2%
		3	<b>Three</b> structural adaptations are indicated.	22%
		2	<b>Two</b> structural adaptations are indicated.	16%
		1	<b>One</b> structural adaptation is indicated.	10%
		0	<b>No</b> structural adaptation indicated	50%
	2. Structure-behavior-function relationship	4	<b>Three</b> features are mentioned but are related to each other.	2%
		3	<b>Two</b> features are mentioned but are related to each other.	16%
		2	<b>Two</b> features are mentioned but are not related to each other.	12%
		1	<b>One</b> feature (i.e. structures) is mentioned.	38%
		0	No structure/behavior/function mentioned	32%
Constructing	3. Spatial isomorphism	4	Drawing resembles the shape of villi shown in the photomicrograph and some internal structures are indicated.	38%
		3	Drawing resembles the shape of villi shown in the photomicrograph but internal structures are not indicated.	20%
		2	Drawing shows the shape of <b>one/two</b> villus and it shows some internal structures.	14%
		1	Drawing shows the shape of <b>one/two</b> villus.	8%
		0	Blank	20%
	4. Use of Conventions	4	<b>Three</b> structures are correctly indicated.	2%
		3	<b>Two</b> structures are correctly indicated.	6%
		2	<b>One</b> structure is correctly indicated.	8%
		1	Attempt to indicate structure but no structure is correctly indicated.	18%
		0	No structure	66%
Transforming	5. Spatial isomorphism	4	Transverse cross-section of several villi is drawn and some internal structures are indicated.	0%
		3	Transverse cross-section of several villi is drawn but internal structures are not indicated.	10%
		2	Transverse cross-section of <b>one</b> villus and some internal structures are drawn.	6%
		1	Transverse cross-section of <b>one</b> villus is drawn.	4%
		0	Blank or wrong drawing	80%
	6. Use of Conventions	4	<b>Three</b> structures are correctly indicated.	0%
		3	<b>Two</b> structures are correctly indicated.	2%
		2	<b>One</b> structure is correctly indicated.	0%
		1	Attempt to indicate structure but no structure is correctly indicated.	0%
		0	No structure is indicated	98%
Critiquing	7. Claims	4	<b>Four</b> claims are made.	8%
		3	<b>Three</b> claims are made.	14%
		2	<b>Two</b> claims are made.	28%
		1	<b>One</b> claim is made.	24%
		0	No claim is made.	26%
	8. Evidence	4	Evidence based on both the drawing and the photomicrograph, which is scientifically sounded.	6%
		3	Evidence based on both the drawing and the photomicrograph, which is not scientifically sounded.	2%
		2	Evidence based on either the drawing or the photomicrograph, which is not scientifically sound.	60%
		1	Evidence related to neither the drawing nor the photomicrograph.	2%
		0	No evidence	30%

The sub-components of constructing and transforming share a similar nature; that is, relying on the skills of drawings. Therefore, they have identical sub-components, spatial isomorphism (sub-component 3 and 5) and use of conventions (sub-components 4 and 6). We further examined students' responses and devised a rubric that can capture a wide range of performance. For example, in the sub-component 3, some students did not draw anything (Level 0); some students drew the shape of one villus without the indication of the internal structures (Level 1); some students drew the shape of one villus with the indication of the internal structures (Level 2); some students drew several villi without the indication of the internal structures (Level 3); some students could draw several villi with the indication of internal structures (Level 4). Therefore, we devised the scores zero to four to capture the range of drawings from those which are not spatially isomorphic to the photomicrograph of villi to those that are spatially isomorphic to the photomicrograph of villi. A similar approach applies to the use of conventions: some students did not indicate structures (Level 0); some students labelled the structures but the indication of structures was incorrect (Level 1); some students indicated one correct structure (Level 2); some students indicated two correct structures (Level 3); some students could indicate three correct structures in their drawings (Level 4). The fine codes aim to capture students' performance ranging from not indicating any structure to indicating three correct structures.

For *interpreting* and *critiquing*, the two coders were also sensitive to theories related to explanation of biological representations involving structure-behaviour-function relationships (Chi et al., 1994; Cheng and Gilbert, 2015). They found that the quantity of students' responses in these two components varied among different students. Therefore, they decided that both the quantity and quality of students' responses should be considered when they studied their visualization competence:

- sub-component 1 (interpreting- number of structural adaptations) and subcomponent 7 (critiquing- claims) concern the number of students' responses,
- subcomponent 2 (interpreting- structure-behaviour-function relation) and subcomponent 8 (critiquing- evidence) concern the quality of students' responses.

For the number of students' responses, they found that some students did not indicate any response (Level 0) while some students indicated four responses (Level 4). Therefore, four levels were formed in sub-component 1 (interpreting- number of structural adaptations) and subcomponent 7 (critiquing-claims) which concern the quantity of students' responses. For subcomponent 2 (interpreting-structure-behaviour-function relation), the coders agreed that interpreting structure-behaviour-function relationships is an important sub-component of visualization competence for photomicrographs. They found that there were five different types of students' responses: no structure, behaviour or function was mentioned (Level 0); one feature such as structures was mentioned (Level 1); two features were mentioned but they were not related to each other (Level 2); two features were mentioned but they were related to each other (Level 3); three features (structure, behaviour and function) were mentioned and were related to each other (Level 4). As Chang (2017) mentioned, critiquing should be based on certain criteria, therefore evidence plays an important role in evaluating whether the representation fulfils any criterion. For subcomponent 8 (critiquing- evidence), it is important that the student compared the features between the photomicrograph of villi and the student's drawing. We identified five different types of responses in the sub-component 8: no evidence was provided (Level 0); evidence provided was related to neither the drawing nor the photomicrograph (Level 1); evidence provided was based on either the drawing or the photomicrograph, which is not scientifically sound and superficial (Level 2); evidence based on both the drawing and the photomicrograph, which is not scientifically sounded and superficial (Level 3); evidence based on both the drawing and the photomicrograph, which is scientifically sounded (Level 4).

Cohen's kappa of 0.735 is obtained, which indicates a good agreement between two coders (Wilkinson, 1999). Disagreements were discussed and resolved. The score in each sub-component adds up together to form a total score for that component. To investigate whether there are interrelations between components and with prior knowledge, Spearman correlation coefficients were obtained (Howitt & Cramer, 2008) by IBM SPSS software.

## Findings

***How do students perform in the four components of visualization competence for a photomicrograph showing villi, namely constructing, interpreting, transforming and critiquing?***

The SVCPQ explores four individual components of how students visualize photomicrographs: *interpreting, constructing, transforming and critiquing*.

In the *interpreting* question, students were asked to interpret the structural adaptations of the photomicrograph of villi and explain how they were related to the behavioural and functional features of villi. In Figure 4, only a few students provided four structural adaptations, and some students gave only one or two structural adaptations. Exactly 50% of the students neither gave structural adaptations, nor indicated the correct structural adaptation shown in the photomicrograph of villi (Figure 5A). As indicated in the number of students scoring three or four in the structure-behaviour-function relationship, students rarely related the features of structure, behaviour and function when they explained the structural adaptations of villi. As justified in the study from Cheng and Gilbert (2013), students should learn how to link these features together to construct a deeper understanding of a scientific phenomenon (Figure 5B).

Figure 4. Percentage of students' performance in interpreting visualization in relation to photomicrograph (N=50)

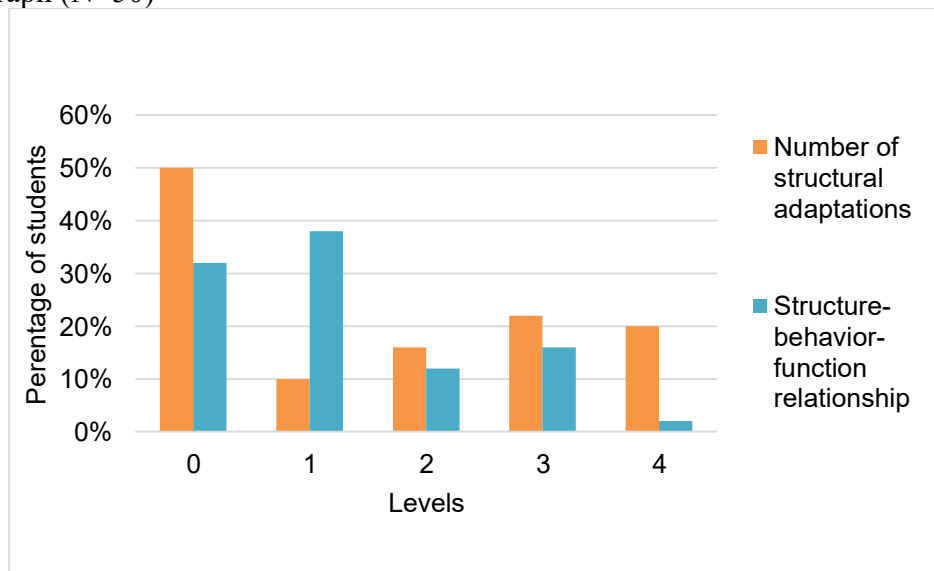
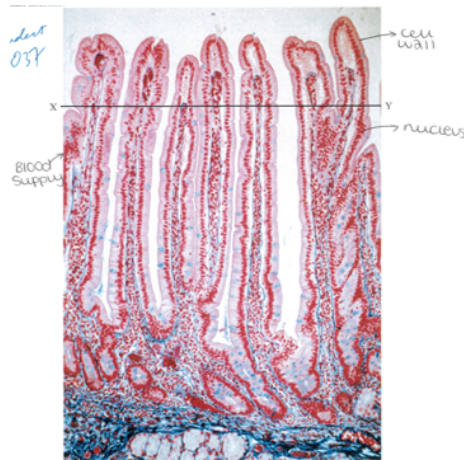
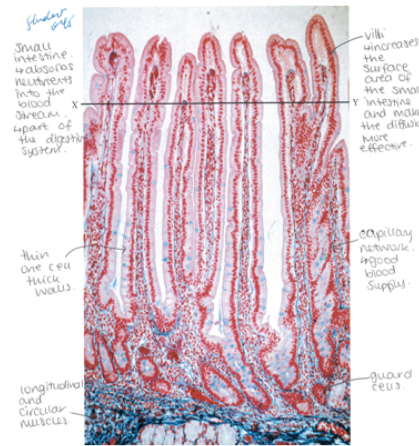


Figure 5. (A) Student 037's response indicates the structures instead of the structural adaptations of villi; (B) Student 045's response indicates more than four structural adaptations

(A)



(B)



In the *constructing* question, students were asked to draw a biological diagram which resembles the referents of the photomicrograph. According to Figure 6, two major trends were observed. Firstly, more than one-third of students were able to draw a biological diagram which was spatially-isomorphic to the referents of the photomicrograph, in which they drew several villi and included internal structures of villi. Less than one-third of students were scored Level 0 to Level 2 in spatial isomorphism, as their construction of diagrams are not based on the photomicrograph. For example, in Figure 7A, Student 011 drew a brief structure of a villus. His drawing contrasts with Figure 7B, where Student 045 indicated the presence of several villi. Secondly, a higher proportion of students tended to give fewer labels, as indicated by the decreasing percentage of students achieving a higher level of use of conventions. This is also supported by the evidence that more than 60% of students cannot label their own biological drawing (Level 0 in use of conventions).

Figure 6. Percentage of students' performance in constructing visualization in relation to photomicrograph (N=50)

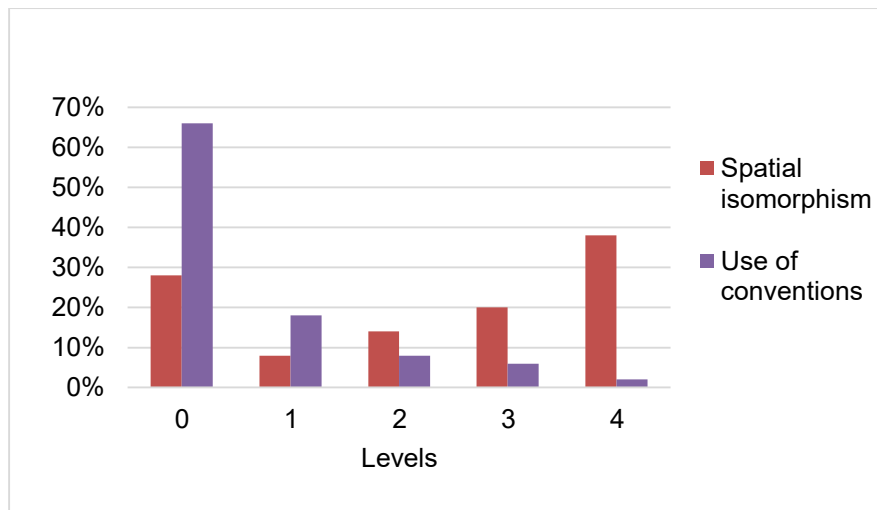
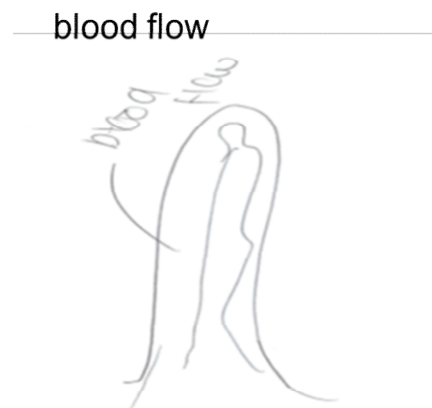
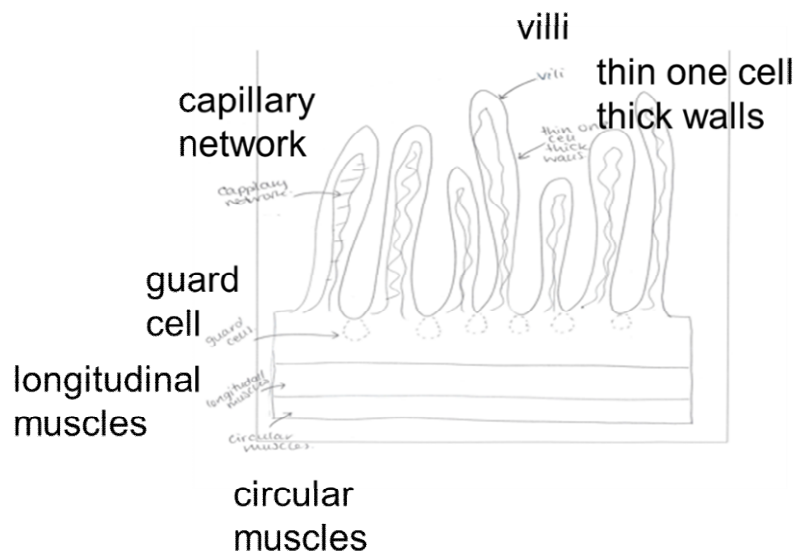


Figure 7. (A) Student 011's response indicates one villus; (B) Student 045's response indicates several villi

(A)

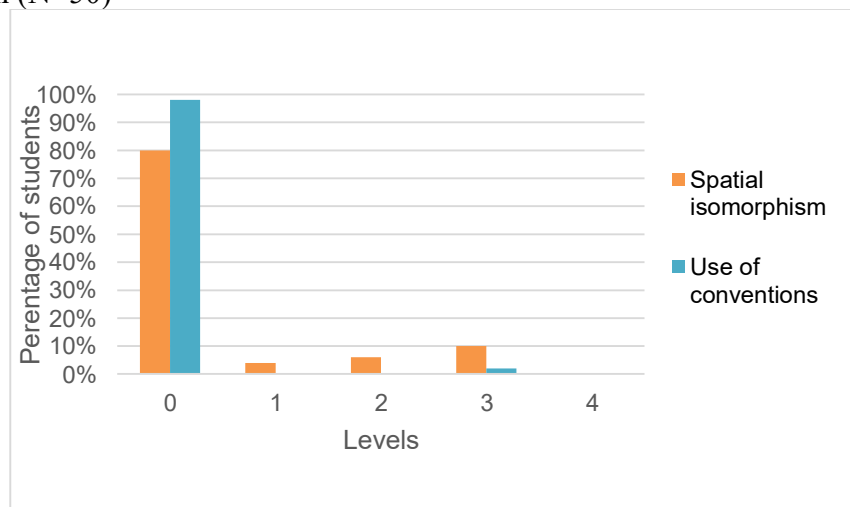


(B)



In the *transforming* question, students are required to visualize the transverse section of a photomicrograph, which shows the longitudinal section of villi. The results of this skill component are shown in Figure 8. Most students cannot visualize the transverse section of villi, as indicated by the evidence that more than 80% of students scored Level 0 in both spatial isomorphism and use of conventions in this skill component. In the sub-component spatial isomorphism, less than 20% of the students scored Level 1 to 3, which means that students encountered difficulties in visualizing the transverse section of villi in relation to the visual clues from the photomicrograph. An equally interesting finding is that more than 90% of students cannot label the structures in their drawing, as indicated by the percentage of students scoring Level 0 in the use of conventions.

Figure 8. Percentage of students' performance in transforming visualization in relation to photomicrograph (N=50)

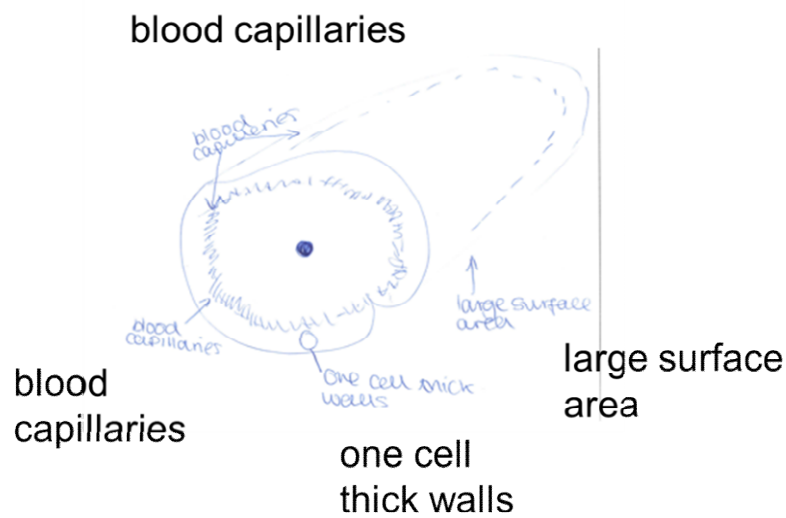


The range of students' performance on this component in Figure 9 can provide a deeper understanding of how students visualize the transverse section of villi in relation to the photomicrograph. For example, Student 013 just drew the transverse section of one villus, which contrasts with the response from Student 008 that indicates the presence of the transverse section of several villi. It might be because they just copied the transverse section from teaching materials, as the representations there often show the transverse section of one villus *only*. The students might feel it too difficult to engage with complex mental imagery, which would require cutting across the axis XY of the photomicrograph and rotating the villi from side view to top-down view. Nevertheless, the response from Student 008 provided an exceptional case: visualizing the transverse section of several villi instead of one villus *only*.

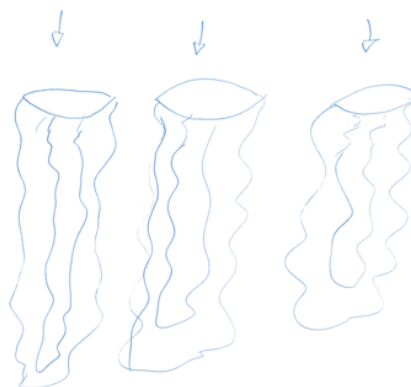


Figure 9. (A) Student 007's response indicates the transverse section of one villus; (B) Student 008's response indicates the transverse section of several villi

(A)

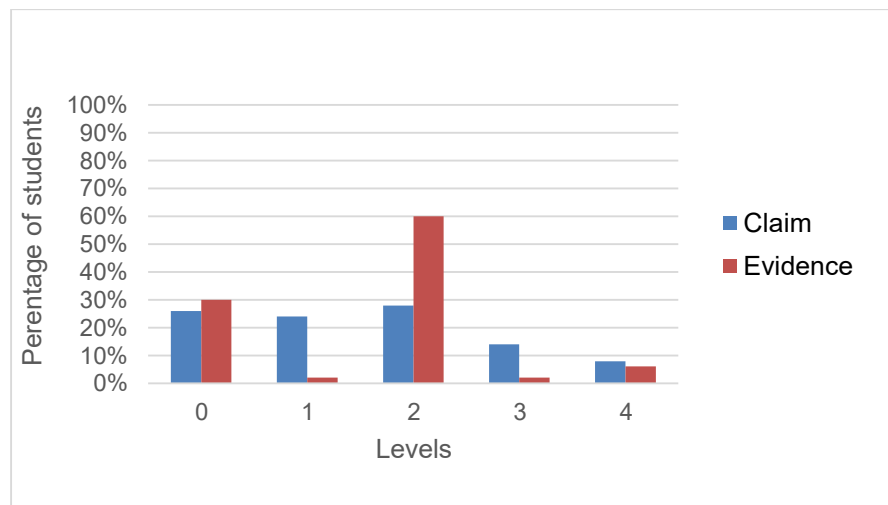


(B)



In the *critiquing* question, the coding rubric examines the number of claims that students raised and whether students warranted their claims by the evidence drawn from both Chris's drawing and the photomicrograph. According to Figure 10, there was a wide range in number of claims, as indicated by an even distribution among all levels in the claim subcomponent. However, 60% of students achieved Level 2 for the evidence subcomponent, showing that they relied on only the drawing or the photomicrograph to formulate their critique. Less than 10% of students scoring Level 3 or Level 4 revealed that students did not integrate the features shown in the photomicrograph and those in the diagram. Such integration of representations seemed to be difficult, as delineated in the finding of the interview.

Figure 10. Percentage of students' performance in critiquing visualization in relation to photomicrograph (N=50)



Although students raised more than one claim, most of their claims were superficial in nature and lacked a scientific argument. The inadequacy in giving solid evidence can also be supported by examples from a student below:

“On one hand, it’s adequate because it’s got labels so still clear. However, it’s quite messy so it’s confusing. Overall, I think its inadequate. (Student 012)” [claim: Level 2; evidence: Level 2]

He commented on the number of labels and the clarity of drawing but did not comment specifically on whether the labels were scientifically correct, or which specific parts of Chris’s drawing misrepresented the referents of the photomicrograph. This contrasts with the response below, which shows rich arguments that are warranted by scientific examples - blood capillaries span across the whole diagram as indicated in the photomicrograph.

“There is not enough villi drawn in the space- there should the villi across the whole section, as well as this blood capillaries need to be drawn all the way through the villi-not just on the edge near the surface as the blood flows all the way through the villi not just on the edge.” (Student 045) [claim: Level 4; evidence: Level 4]

Table 3 below shows the mean and standard deviation of the levels of each sub-component and component of photomicrograph visualisation. Students performed better in constructing and critiquing visualization in relation to the photomicrograph of villi, with performance on these two skills roughly equivalent. In comparison, interpreting is a more difficult skill than constructing and critiquing, as its mean score is around 0.7 lower. The most difficult skill for students is transforming, which has a significantly lower score compared to the other three components.

Table 3. Descriptive statistics of students' performance in SVCPQ

Components	Criteria	Mean	S.D.
(a) Interpreting	1. Number of structural adaptations	1.16	1.31
	2. Structure-behavior-function relationship	1.18	1.12
	Total	<b>2.34</b>	2.12
(b) Constructing	3. Spatial isomorphism	2.48	1.55
	4. Use of Conventions	0.60	1.03
	Total	<b>3.08</b>	2.21
(c) Transforming	5. Spatial isomorphism	0.46	0.99
	6. Use of Conventions	0.06	0.42
	Total	<b>0.52</b>	1.16
(d) Critiquing	7. Claims	1.54	1.25
	8. Evidence	1.52	1.13
	Total	<b>3.06</b>	2.19

***What component(s) of students' visualization competence for a photomicrograph showing villi is/are correlated to each other?***

To examine the correlations among components, Spearman correlation tests were performed. The result is shown in Table 4.

Table 4. Descriptive statistics of students' performance in SVCPQ

		Interpreting	Constructing	Transforming	Critiquing
Interpreting	$r_s$	1.000	.467**	.146	.545***
	$p$	.	.001	.312	.000
	$n$	50	50	50	50
Constructing	$r_s$		1.000	-.018	.340*
	$p$		.	.903	.016
	$n$			50	50
Transforming	$r_s$			1.000	-.035
	$p$			.	.812
	$n$				50
Critiquing	$r_s$				1.000
	$p$				.
	$n$				50

\*  $p \leq .05$ ; \*\*  $p \leq .01$ ; \*\*\*  $p \leq .001$ .

Moreover, students' performance in interpreting the photomicrograph was highly correlated with constructing a biological diagram that resembles the photomicrograph [ $r_s = 0.467$ ,  $p < 0.01$ ] and strongly correlated with critiquing whether a representation resembles the photomicrograph [ $r_s = 0.545$ ,  $p < 0.001$ ]. The component of constructing is also correlated with the component of critiquing [ $r_s = 0.340$ ,  $p < 0.05$ ]. These findings show that constructing, interpreting and critiquing are interrelated. However, the skill of transforming is not correlated to one of the other components of visualizing photomicrographs. Transforming is a special skill that demands more mental processing. In this context, it involves imagining cutting the cross-section of a longitudinal section of villi and looking at the transverse section from a top-down perspective.

To provide a deeper understanding of students' visualization competence, the correlations among sub-components were examined. According to Table 5, sub-components within one component correlate with each other, because they belong to one skill of visualizing photomicrographs (see the shaded box). For example, '1. Number of structural adaptations' is significantly and strongly correlated to '2. Structure-behaviour-function relationship' [ $r_s = 0.569, p < 0.001$ ] because they both are the subsets of interpreting photomicrographs.

Sub-components 1, 2, 4, 7 and 8 require students to draw on their textual resources from working memory in writing responses in the questionnaire. '1. Number of structural adaptations' is significantly correlated to 'Use of Conventions (constructing)' [ $r_s = 0.429, p < 0.01$ ], '7. Claims' [ $r_s = 0.339, p < 0.05$ ] and '8. Evidence' [ $r_s = 0.352, p < 0.05$ ]. Similarly, '2. Structure-behaviour-function relationship' is found to be strongly correlated with '4. Use of Conventions (constructing)' [ $r_s = 0.609, p < 0.001$ ], '7. Claims' [ $r_s = 0.633, p < 0.001$ ] and '8. Evidence' [ $r_s = 0.609, p < 0.001$ ]. '4. Use of Conventions (constructing)' is also significantly correlated to '7. Claims' [ $r_s = 0.353, p < 0.05$ ] and '8. Evidence' [ $r_s = 0.457, p < 0.01$ ]. These results might be accounted by the fact that students may draw on their textual resources from working memory to translate across the skills of constructing, interpreting and critiquing.

Table 5. Correlation matrix among sub-components of visualizing photomicrographs

Components		<i>Interpreting</i>		<i>Constructing</i>		<i>Transforming</i>		<i>Critiquing</i>	
Sub-components		1. Number of structural adaptations	2. Structure-behavior-function relationship	3. Spatial isomorphism	4. Use of Conventions	5. Spatial isomorphism	6. Use of Conventions	7. Claims	8. Evidence
1	$r_s$	1.000	.569***	.240	.429**	.299*	.096	.339*	.352*
	p	.	.000	.094	.002	.035	.507	.016	.012
	n	50	50	50	50	50	50	50	50
2	$r_s$		1.000	.361*	.609***	-.071	.005	.633***	.609***
	p		.	.010	.000	.622	.971	.000	.000
	n		50	50	50	50	50	50	50
3	$r_s$			1.000	.521***	.022	.159	.176	.218
	p			.	.000	.879	.269	.221	.129
	n			50	50	50	50	50	50
4	$r_s$			.**	1.000	-.161	.224	.353*	.457**
	p			.	.	.263	.118	.012	.001
	n				50	50	50	50	50
5	$r_s$					1.000	.262	-.017	-.099
	p					.	.066	.909	.493
	n					50	50	50	50
6	$r_s$						1.000	.071	.245
	p						.	.623	.087
	n						50	50	50
7	$r_s$							1.000	.722***
	p							.	.000
	n							50	50
8	$r_s$					-			1.000
	p								.
	n								50

\*  $p \leq .05$ ; \*\*  $p \leq .01$ ; \*\*\*  $p \leq .001$ .

In contrast, ‘3. Spatial isomorphism (constructing)’ is *not* significantly correlated to ‘5. Spatial isomorphism’ [ $r_s = 0.022, p > 0.05$ ]. Although both sub-components provide an understanding of how students draw the diagram resembling the referents of the photomicrograph of villi, students’ performance in drawing a longitudinal section diagram which is spatially isomorphic to the photomicrograph of villi does not relate to that in drawing a transverse section of a diagram along the axis of the photomicrograph. This finding is different from the finding from Chang (2018): that is, students’ skills in generating representations to represent their ideas are correlated with those for creating new representations to complement and replace another representation. However, it should be noted that Chang’s (2018) finding may only be relevant to the context of her study (on students’ skills in utilising representations in general).

## Discussion and Implications

### *Visualization competence for photomicrographs*

Visualization refers to the skills that students employ when using mental imagery to think about a scientific phenomenon (Gilbert, 2004). This empirical research study has built on the construct “visualization competence” (Chang, 2017) to measure students’ skills in utilising photomicrographs. These include *constructing* a biological drawing that resembles the photomicrographs, *interpreting* the structures of cells and tissues in the photomicrographs, *transforming* a longitudinal section into transverse section, *critiquing* whether a drawing can represent a photomicrograph of villi (see Figure 2). These four modified components of visualization competence have been shown to capture effectively a range of students’ ability. We also developed a tool, Students’ Visualization Competence for Photomicrograph Questionnaire, to measure students’ skills in visualizing a photomicrograph of villi. The construct and the tools can potentially be modified and applied to measure students’ visualization competence for other types of photomicrographs.

The results have shown that when compared to *interpreting* and *transforming*, students scored higher in *constructing* and *critiquing* representations in relation to photomicrographs. This contrasts with the findings from Chang and Tzeng (2017), which showed that students found it challenging to critique a visualization. In their instrument, the critiquing item requires students to evaluate which model adequately represents the arrangement of gas particles in a flask. However, in the SVC PQ, students have access to two different types of representations, a student’s drawing and the photomicrograph of villi. The student’s drawing is less abstract than the photomicrograph, so it is likely that the drawing can activate students’ constructive resources to critique it (diSessa and Sherin, 2000; Chang and Tzeng, 2017). Therefore, students can apply criteria to evaluate the differences between these two representations.

*Interpreting* and *transforming* are comparatively more difficult skills for students to comprehend, as these skills might demand more cognitive processing in the capacity of working memory (Schnotz & Bannert, 2003). For *interpreting*, students were required to generate a structure-behaviour-function propositional representation (Cheng & Gilbert, 2015; Chi et al., 1994) for the photomicrograph of villi, through which they transferred their understanding of the texts to the photomicrograph. For *transforming*, the process of creating a mental image of a transverse section is more complex than that of a longitudinal section, as this process involves students visualizing villi from the top-down perspective, cutting open the villi transversely, and imagining the appearance of the transverse section of villi. Transforming is a skill that involves both spatial visualization and spatial rotation: spatial visualization refers to the ability to visualize 3D images from 2D image; spatial rotation refers to the ability to understand what a 3D object looks like from a different perspective

(Barnea, 2000). *Interpreting* and *transforming* took more steps than those when students constructed visualizations in relation to the photomicrographs. As a result, students performed less well in these two skills in utilising the photomicrograph of villi.

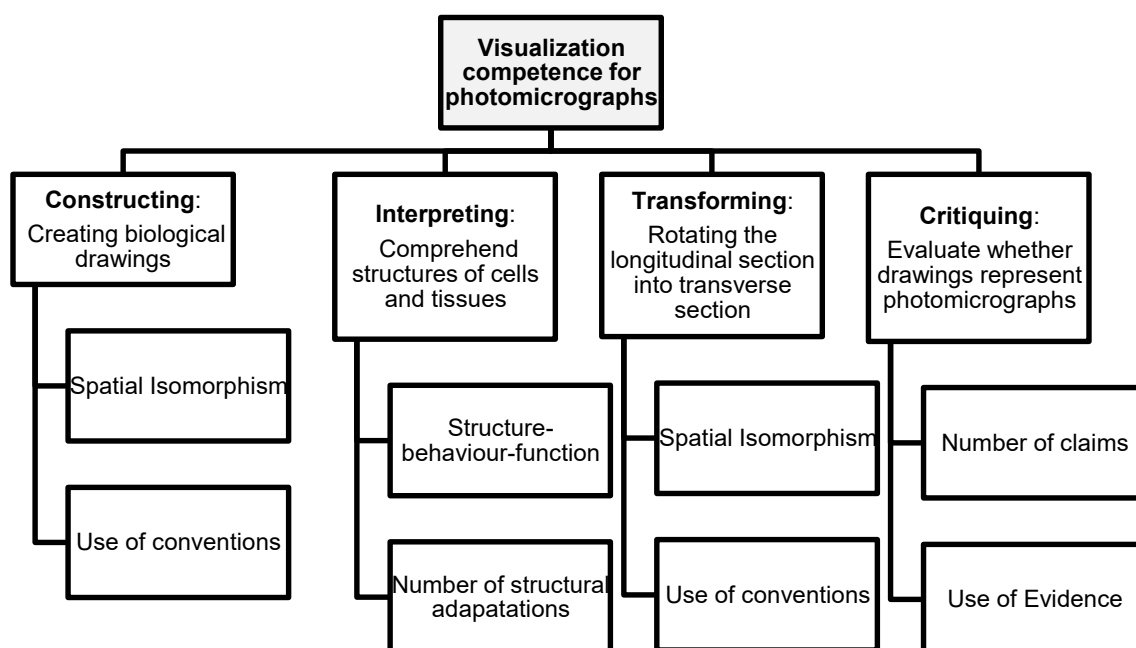
### ***Sub-components of visualization competence for photomicrographs***

Students' performance on sub-components within each skill component of visualization competence for the photomicrograph of villi were also examined in this study. The sub-components which rely heavily on textual processing were found to be significantly correlated with each other. For example, '1. Number of structural adaptations' is significantly correlated to '4. Use of Conventions (constructing)', '7. Claims' and '8. Evidence', and '2. Structure-behaviour-function relationship' is found to be strongly correlated with '4. Use of Conventions (constructing)', '7. Claims' and '8. Evidence'. However, neither '3. spatial isomorphism (constructing)' or '5. spatial isomorphism (transforming)' is significantly correlated to the sub-components of another skill component, especially those which require textual processing. These findings align with the notion from Schnotz and Bannert (2003) that textual processing and pictorial processing are situated in different pathways in the compartment of working memory. In other words, students who know how to use visual information to represent the photomicrograph do not necessarily know how to use verbal information to represent the referents of the photomicrograph. This is supported by the evidence that '3. spatial isomorphism (constructing)' is not significantly related to '1. Number of structural adaptations'. The number of textual descriptions provided did not show a significant relationship with their drawings. By contrast, students' ability to use textual information to interpret visualization in relation to the photomicrograph is associated with that required to critique visualization in relation to the photomicrograph. '7. Claims' and '8. Evidence' of the major component "critiquing" are significantly correlated to both '1. Number of structural adaptations' and '2. Structure-behaviour-function relationship' of the component "interpreting".

### ***Implications, limitations and future directions***

Previous research studies have investigated students' performance in different components of visualization competence (Chang and Tzeng, 2017; Chang, 2018). However, their conceptualization cannot be applied to the examination of students' visualization competence for photomicrographs. The current study contributes to the literature by modifying the four major components of visualisation competence to measure students' visualization competence for photomicrographs as well as delineating their sub-components (see Figure 11). The findings are different from previous findings (i.e. Chang and Tzeng (2017); Chang (2018)) because the performance of visualization competence can be dependent on the abstractness of representations, the domain of representation and the nature of the task. More importantly, the findings show that significant correlations existed among sub-components that draw on students' textual resources. This aligns with previous findings that visual and textual information are processed in two different pathways (Schnotz and Bannert, 2003; Pun and Cheung, 2021). In the components "constructing" and "transforming", performance in the use of conventions is lower than that in the use of spatial isomorphism. As supported by the correlation matrix, the sub-components "use of conventions" (subcomponents 4 and 6) in these two components can be developed together with the other two components "interpreting" and "critiquing". Although the current study did not investigate how to promote students' visualization competence for photomicrographs, its results provide insights on designing teaching intervention programmes to improve the performance of students' visualization competence for photomicrographs. The results also invite future studies on focusing both visual and verbal resources when teachers help students develop their visualization competence for photomicrographs.

Figure 11. Components and sub-components of visualization competence for photomicrographs



Moreover, Figure 11 forms a framework for teacher educators to design teaching and assessment materials that help students advance their visualization of photomicrographs. In science classrooms, teachers should encourage students to draw and label biological diagrams that represent the structures in the photomicrograph, relate the structural features to the behavioural and functional features, transform across longitudinal section and transverse section, and critique their peers' biological drawing of the photomicrographs. One of the important findings of this study is that when students drew the longitudinal section or transverse section of villi, they did not put a lot of labels in their diagrams. In view of this, teachers should ask students to correspond the labels in textbook diagrams to those in the photomicrographs, which provide an assessment opportunity for teachers to examine whether students have acquired the skills of utilising photomicrographs (Waldrip, Prain, & Carolan, 2010). More importantly, teachers could consider starting instruction on photomicrographs by asking students to construct a biological diagram or to critique whether a drawing resembles a photomicrograph. After fostering these two skills, teachers could scaffold students to develop the skills to relate the behavioural and functional features to the structural features shown in the photomicrograph, as well as visualizing the three-dimensional structure and transverse section of the biological structures shown in the photomicrographs.

One of the limitations of this study is the small number of students involved. Instead of making attempt to generalise the findings to the population, this study aims to illustrate different levels of skills components in visualizing photomicrographs and some patterns of correlation. Moreover, due to the exploratory nature of this study, the results may only apply to the visualization of the photomicrograph of villi. It is unknown whether students would demonstrate similar patterns of visualization competence when they utilise photomicrographs of other types of cells. There might be differences between students' visualization competence for photomicrographs showing animal cells and those showing plant cells, as students may prefer studying animals over plants (Wandersee & Schussler, 1999). Therefore, future research studies can be carried out on students' visualization competence for photomicrographs showing different types of structures.



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