International Journal of Science Education
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tsed20

Students' Visualization of Diagrams Representing the Human Circulatory System: The use of spatial isomorphism and representational conventions

Maurice M. W. Cheng[a] & John K. Gilbert[bc]
[a] Faculty of Education, University of Hong Kong, Hong Kong
[b] King's College London, London, UK
[c] University of Reading, Reading, UK

Published online: 20 Nov 2014.

International Journal of Science Education, 2015
Vol. 37, No. 1, 136–161, http://dx.doi.org/10.1080/09500693.2014.969359

Students' Visualization of Diagrams Representing the Human Circulatory System: The use of spatial isomorphism and representational conventions

Maurice M. W. Cheng[a*] and John K. Gilbert[b,c]
[a]*Faculty of Education, University of Hong Kong, Hong Kong;* [b]*King's College London, London, UK;* [c]*University of Reading, Reading, UK*

This study investigated students' interpretation of diagrams representing the human circulatory system. We conducted an interview study with three students aged 14–15 (Year 10) who were studying biology in a Hong Kong school. During the interviews, students were asked to interpret diagrams and relationships between diagrams that represented aspects of the circulatory system. All diagrams used in the interviews had been used by their teacher when teaching the topic. Students' interpretations were expressed by their verbal response and their drawing. Dual coding theory was used to interpret students' responses. There was evidence that one student relied on verbal recall as a strategy in interpreting diagrams. It was found that students might have relied unduly on similarities in spatial features, rather than on deeper meanings represented by conventions, of diagrams when they associated diagrams that represented different aspects of the circulatory system. A pattern of students' understanding of structure–behaviour–function relationship of the biological system was observed. This study suggests the importance of a consistent diagrammatic and verbal representation in communicating scientific ideas. Implications for teaching practice that facilitates learning with diagrams and address students' undue focus on spatial features of diagrams are discussed.

Keywords: *Diagrammatic representation; Dual coding theory; Structure–behaviour–function understanding; Visualization*

*Corresponding author. Faculty of Education, University of Hong Kong, Hong Kong. Email: mwcheng@hkucc.hku.hk

Introduction

Learning of many human biology concepts involves an understanding of how body structures undergo certain processes and achieve certain physiological functions that are essential for survival. The four-chamber human heart with all blood vessels (the cardiovascular system) is modelled as the 'double circulation system'. It separates the oxygenated blood from the deoxygenated blood before it circulates around the body. It also allows blood pressure high enough to circulate around the systemic circulation.

Learning of human circulatory system is important in biology. Not least because it is a key human physiological system, it is also important because understanding the system is a key to the learning of other important biological concepts, for example, the transport and exchange of materials in the human body, gaseous exchange, and the lymphatic system. An understanding of cardiovascular disease and their treatment is also based on concepts related to the circulatory system.

Biology concepts are not only represented by words (like the description in the above paragraph) in printed or on-screen media. They are also represented visually, for example, in the form of different diagrams. According to dual coding theory (Paivio, 1986), verbal and visual means of presenting information facilities learning. It is due to the synergy of the mental verbal system and the mental visual system. Multiple representations play an essential role in communicating disciplinary knowledge for students' learning. Among all the possible forms of representation, this paper focuses on the role of textbook diagrams and some ways students might have interpreted them, because textbooks play a major role in science education in many countries.

Learning the human circulatory system, like learning many other scientific concepts, is demanding (Ainsworth & Loizou, 2003; Arnaudin & Mintzes, 1985; Assaraf, Dodick, & Tripto, 2013; Pelaez, Boyd, Rojas, & Hoover, 2005; Sungur & Tekkaya, 2003). A reason for the difficulty is that learning the system involves an integrated understanding of different representations of the system. They include diagrams representing, for example, the four-chamber heart, the system of blood vessels in the human body, the blood flow in the pulmonary and systemic circulations, relative lumen size of arteries, veins, and capillaries. Students do not only have to understand each of the diagrams, but also have to understand the relationship between the diagrams, and form a holistic view of the system.

Previous studies revealed that students' understanding of the human circulatory system could be problematic. For example, it was found that, based on students' drawing, some of them might have believed that blood circulation involves a drop of blood circulating around the whole body before going back to the heart. They may not be able to appreciate the significance of the pulmonary circulation (Arnaudin & Mintzes, 1985; Pelaez et al., 2005). Nevertheless, little is known about how students interpret diagrams and the relationships between diagrams when they learn the human circulatory system. Unlike many existing studies, this study particularly investigated how students associated multiple diagrams that represented different aspects of the same science concepts. Such a capability is commonly called for, but sometimes neglected, in learning science (Liu, Won, & Treagust, 2014).

A way of conceptualizing different diagrams is to put them into a spectrum of different degrees of abstraction (Pozzer & Roth, 2003). Many diagrams, however, include a mixture of concrete and abstract elements. It may be more fruitful to consider the ways in which a diagram represents its referents. It has been proposed that a diagram represents through the use of two characteristic features, namely its conventions and spatial isomorphism (Hegarty, 2011; Hegarty, Carpenter, & Just, 1991). In this study, the ways that students interpret representational conventions and the spatial isomorphic features of diagrams were investigated. This study aimed to answer the general research question, 'How did students interpret diagrams and associate diagrams in their learning of the human circulatory system?'

In order to gain an in-depth understanding of students' mental visualization of the circulatory system and their ways of interpreting diagrams, we collected the data through three clinical interviews of Year 10 students in a Hong Kong secondary school. Its intake has an average of students' academic achievement for the territory. The students were selected based on their biology exam scores, from the top 10th, the 45th–50th, and the lowest 10th percentile of their cohort in this school. We probed into students' mental visualization through their drawing, their explanation of their drawing and their interpretation of diagrams used during the classroom teaching. The study further demonstrated the contribution of dual coding theory in enhancing our knowledge of students' learning and some possible ways that they interpret diagrams.

Dual Coding Theory and the Circulatory System

Dual Coding Theory

In the use of textbooks, learning about the circulatory system takes place by reading and by viewing diagrams. Dual coding theory discusses the relationship between these representational systems. The most important tenets of dual coding theory are that (i) there are two independent but interconnected functional systems, namely the verbal system and visual system for information processing, and (ii) information can be recalled and manipulated more easily if it is encoded in both systems (Paivio, 1986, 2007). The detail of the theory that is relevant to science education research has been discussed in Cheng and Gilbert (2014). In short, information processing can be regarded as making of connections between different mental representations in the verbal system and in the visual system. In this study, being able to visualize can be regarded as:

- Making connections between mental visual representations within the visual system. These connections are called associative connections. Reading a diagram involves forming a mental visual representation in the mental visual system. Such a formation may be guided by students' existing mental visual representation (or prior knowledge). Interpretation of the relationship between diagrams thus involves making associative connections between mental visual representations triggered by the diagrams. Learning the circulatory system, in other words, involves the capability in visualizing various diagrams that represent different aspects of the system. These involve the making of associative connections.

- Making connections between mental visual representation and mental verbal representation. Such connections are called referential connections. Giving a verbal name to a structure or drawing a structure based on its name involves the making of referential connections. Learning many biological concepts involves verbalizing processes and functions based on diagrams that represent structures. For example, in learning the circulatory system, students would have to describe in words how blood flows around the body based on diagrams that represent some key blood vessels and key organs such as the heart, lungs, and kidneys of a human body.

Learning the Circulatory System

Learning the human circulatory system is very challenging. At the system level, students would have to appreciate the major functions of the whole system, that is, to facilitate the transport and exchange of materials. At the organ level, students would have to relate the structures and functions of individual organs. Meanwhile, they would have to appreciate how different functions and structures of individual organs/tissues are orchestrated to serve the system functions.

Chi, De Leeuwa, Chiu, and Lavancher (1994) elaborated the complexity of the topic. They analysed the system in terms of its constituent components. Each component has its specific 'local' features: structure (what it is), function (what it serves), and behaviour (what it does). Figure 1 exemplifies the features of two components: arterioles and capillaries. The features are abbreviated as S, F, and B, respectively, in the succeeding discussion.

Understanding only these two components entails not only relating the features within a single component, for example, it is the *slow* movement of blood (B) and the *one-cell* thick wall of capillaries (S) that *facilitates* the exchanges of materials (F), but also making meaningful linkages across features of these two components. For

<u>*Arterioles*</u>

Structure (S)	:	hollow tubes
Function (F)	:	to relay blood from arteries to capillaries
Behaviour (B)	:	to allow blood to pass through

<u>*Capillaries*</u>

Structure (S)	:	one-cell thick hollow tubes
Function (F)	:	to facilitate exchanges of materials between body cells and blood
Behaviour (B)	:	to allow blood to pass through slowly and materials to pass through

Figure 1. Features of capillaries and arterioles (Based on Chi et al., 1994)

example, capillaries (in terms of their 'structure') are sub-branches of arterioles (in terms of their 'function', see Figure 1) (for a similar analysis of a heart atrium and valves, please refer to Chi et al., 1994, p. 444.). Such analyses of the relationships between features of components can be extended to other components. For example, the systemic circulation and the pulmonary circulation have their own structures, functions, and behaviours. Other than making linkages between features of single components and across different components, a deep understanding of the system also involves appreciating how these local features contribute to the overall system-wise function. Experts could be characterized by having an integrated understanding of SBF of a system and its components, whereas novice tended to focus on structures in isolations (Hmelo-Silver, Marathe, & Liu, 2007). Given the complexity of the learning, there is little wonder that school students and even prospective elementary teachers were found to hold a single loop circulation (e.g. blood goes from the heart to the toe and then returns to the heart, on and on) rather than the idea of double circulation (Arnaudin & Mintzes, 1985; Pelaez et al., 2005). That is, the structures and the flow of blood that did not support the functions of the circulatory system.

Learning of the circulatory system also demands reading text and reading about a variety of related diagrams. It has been reported that some students could rely only on their verbal memory in learning some scientific ideas. While their verbal recall may be scientifically correct, when they are asked to draw out their verbal explanation, their drawings were indeed unscientific translations from the verbal recall. That is, students memorized the verbal information without making a referential connection to a mental visual representation that was scientifically acceptable. Such a finding demonstrates the application of the dual coding theory in investigating students' visualization of a scientific idea. For example, in their learning of the electron-sea model and the malleability of metals, some students could recall verbally that the 'electrons are in the surroundings of metal cations'. These verbal recalls would have been judged scientifically accurate. Nevertheless, in their drawing, the electrons were enveloping the whole metal cation lattice rather than surrounding each of the metal cations; there was no electron between metal cations in the lattice (Cheng & Gilbert, 2014). As learning many physiological processes and functions demands accurate spatiality of structures, it would be worthwhile to investigate some ways that students translate verbal and visual representations of structures and behaviours of biological components.

Diagrammatic Representations

A diagram can sometimes be classified as being concrete or being abstract, or somewhere between the two extremes. The concrete–abstract continuum applies to many photographs and line drawing such as electric circuit diagrams. Nevertheless, a diagram that includes both concrete and abstract elements may not fit well into the continuum. Also, concrete diagrams may not necessarily mean easily comprehensible. A photograph, though being concrete, can be challenging for students' interpretation (Pozzer-Ardenghi & Roth, 2005). We believe that some line drawings such as road signs or the heart-shape, though being abstract, are often readily comprehensible. Therefore, the amount of details in a diagram at times does not explain well its ease of comprehension. There have been other ways of categorizing diagrams (e.g. Bertin, 2011; Lohse, Biolsi, Walker, & Rueter, 1994). It is important to identify a scheme that could be revealing to students' visualization of diagrams that were used in the context of teaching and learning of the biological topic investigated in this study.

Hegarty (2011) proposed that there are two ways that diagrams represent, namely, through the use of spatial isomorphism and representational conventions (also in Hegarty et al., 1991). Spatial isomorphism means that the structural and spatial relationship of the elements in a diagram resembles their referents. For example, the photograph of a biological specimen is highly isomorphic with its referent. The feature of spatial isomorphism in diagrams shed light on how diagrams facilitate our thinking. There have been a number of studies explaining the functional roles that diagrams serve in facilitating our cognitive processing (e.g. Cheng, 1996; Hegarty, 2004; Scaife & Rogers, 1996). They were all based on the idea that diagrams are superior to verbal text, because diagrammatic representations make the search and recognition of elements much easier (Larkin & Simon, 1987). Such superiority is endowed by the nature of the way diagrams represent their referents, that is, by

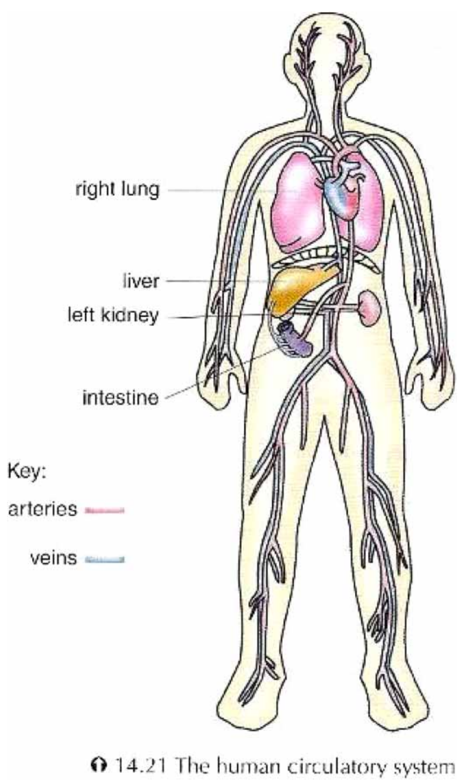


Figure 2. A system diagram
(Source: Chan, Chu, & Kwong, 2006, p. 184)

'[preserving] explicitly the information about the topological and geometric relations among the components' (p. 66). This is the explicitness of information arranged spatially that renders information search and recognition effective.

Take a textbook diagram that represents some of the gross structures of the human circulatory system (Figure 2) as an example (it will be called 'system diagram' in this paper thereafter); it shows very explicitly the spatial location and the gross appearance of the heart, lungs and some blood vessels that go to the upper and lower part of the body. It also shows blood vessels that connect the kidneys. This diagram preserves the spatial relationship between organs in a way very similar to that of the human body. It is believed that the same information could (if at all) only be represented by extremely lengthy sentential text description. In that sense, the diagram is more effective than a piece of would-be verbal text in representing the equivalent piece of information, that is, the gross appearance and spatial relationship of the lungs, hearts, blood vessels and the blood flow.

Diagrams also represent their referents through the use of conventions, such as colours, symbols, icons, or notations. They are embedded in diagrams such that dynamic, non-structural features or processes (or behaviours) could be represented. For example, blood vessels that carry oxygenated blood are conventionally represented by red; those carry deoxygenated blood are conventionally in blue (as in Figure 2). In other contexts, a 'magnifying glass' as an icon can be used to link up macro and submicro phenomena, a complicated structure can be reduced to a simple or geometric shape, etc.

The use of conventions and spatial isomorphism is evident in many biological diagrams. For example, Figure 3 represents the blood flow in different types of blood vessels and an organ. The flow of blood through the artery and the vein is represented by arrows, that is, as a convention. Yet, the blood flow from the artery to the vein and the organ in which capillaries embedded are not represented. The

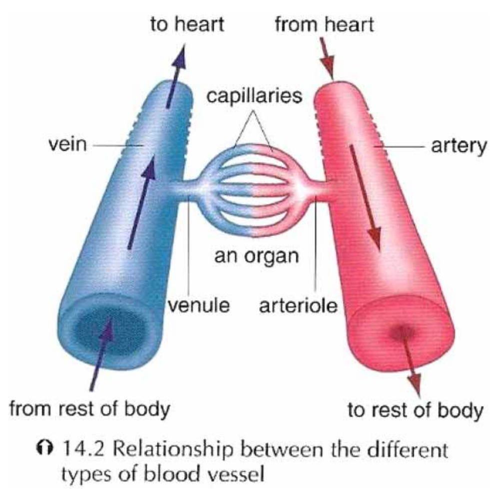


Figure 3. A diagram representing blood flow in different types of blood vessels (Chan et al., 2006, p. 172)

relative lumen size of the artery, the vein, and the capillaries are represented by spatial isomorphism, that is, the lumen size of the vein is larger than that of the artery.

It would have been a challenge to put diagrams like Figures 2 and 3 into single points in a concrete–abstract continuum—some of their elements are concrete while some are more abstract. Interpretation of the diagrams would be fruitful only if readers are able to identify which elements in the diagrams are spatially isomorphic to the referents and which are conventions (so that irrelevant spatial information can be ignored).

Demands and Potential Challenges in Visualizing Diagrams

Students would come across many diagrams that represent different aspects of the circulatory system during their learning. We argue that learning of the system demands an integrated understanding of different relevant diagrams (Ainsworth, 2008; Won, Yoon, & Treagust, 2014). It is expected that students should not only be able to visualize the blood flow as represented in Figure 3 but also to identify the structure and spatial location of blood vessels and organs in Figure 2. In this way, the blood flow diagram (Figure 3) helps students to construct deeper understanding based on the gross structure in Figure 2 (Ainsworth, 2008). Students should also be able to associate the diagrams mentally such that they can visualize how the generalized blood flow (represented in Figure 3) occurred specifically in the human body (represented in Figure 2).

We envisaged that there were at least two challenges students would face when interpreting the blood flow diagram (Figure 3): (a) The diagram represents a generalized idea about the direction of blood flow. It did not necessarily mean in a particular pair of veins/arteries in human bodies. Readers would have to identify the conventions (i.e. arrows, colour of blood vessels) that represented the blood flow in different blood vessels and also have to apply such a generalized idea of blood flow in reading other diagrams representing the circulatory system, for example, Figure 2. The parallel artery and vein, however, do not necessarily represent the exact spatial arrangement of arteries and veins in the human body. It is postulated that some students might take the spatial features literally. It would lead to a visualization of the body or blood flow that was alternative to that accepted by canonical science. Indeed, it has been reported that students could interpret the shape of a curve in a graph (which represents through adopting conventions) as being the shape of a hill. In that sense, they were relying on spatial features of a convention, for example, upward and downward lines, when interpreting a curve (diSessa, Hammer, Sherin, & Kolpakowski, 1991). (b) The caption was not specific in guiding readers to read the diagram intended by the diagram designers. The word 'relationship' could refer to a *structural* relationship only (i.e. to the relative size of different blood vessels and how they are connected) or the sequence in which blood flows through them (the *behaviour*). Without specific guidance, it would leave readers to interpret the diagram as they saw fit. It would thus be worthwhile to investigate how students might possibly associate the caption with the diagram.

In view of the above discussion that an understanding the human circulatory system involves the capability to visualize various diagrams representing the system and that diagrams represent through spatial isomorphism and by the use of conventions, this study thus sought to answer the following question:

> How do students associate a diagram that is highly spatial isomorphic in representing the gross structure of human body (Figure 2) and a diagram that heavily uses conventions in representing blood flow in the circulatory system (Figure 3)?

An answer to the question is significant not only in leading to an understanding of students' interpretation of diagrams on the topic of human circulation, but also to some general issues about students' reading of diagrams when they learn science.

Research into Students' Interaction with Diagrams—Different Approaches, Same Goal

There are two major approaches to develop an understanding of how students interact with diagrams. One approach, which is based more on cognitive processing, investigates how individual students interpret diagrams (e.g. Cook, Carter, & Wiebe, 2007; Novick & Catley, 2014; Schönborn & Anderson, 2009; Viennot & Kaminski, 2006). As diagrams are often accompanied by text, extensive research in psychology has been conducted to investigate how students comprehend text and diagrams (Mayer, 2009; Schnotz, 2005). This line of research has been shown to be essential to inform the design of diagrams, and strategies for teaching and learning with diagrams (see also Hegarty, 2011). Another approach adopts a sociocultural stance and focuses on the meaning-making processes when readers interact with diagrams. Based on Peircian semiotics, these processes involve the inter-relationship between diagrams, their referent objects and ideas generated from the diagrams and/or objects. It acknowledges that meanings are not embedded in diagrams but are actively created by readers. These ideas have informed development of classroom practice that facilitated students' learning by involving students in interacting with physical phenomena and constructing, defending, and interpreting diagrams and various kinds of representations (Tytler, Prain, Hubber, & Waldrip, 2013).

These two approaches adopted different unit of analysis and are complementary to advancing our knowledge of learning with diagrams (Taber, 2014). The sociocultural approach has been shown to be very fruitful in understanding how a group of learners was facilitated in a community of practice, for example, in the contexts of learning in laboratory inquiry and in classroom teaching. We agree that students do actively construct meaning when they read texts and diagrams. We believe, as far as teaching materials are concerned, it is important that they have a clear and distinctive intended message (rather than being too open for different interpretations that are deviant from the scientific meaning intended by authors). One way of ensuring quality teaching and learning is to scrutinize how diagrams used in teaching materials might have facilitated, or hampered, learning. Thus, it is essential to develop a better understanding of how individual students interpret diagrams, so that suitable teaching strategies can be developed to cater for students' need. For example, Waldrip and Prain (2013) emphasized that during the planning phase, among other tasks, teachers would have to identify key scientific concepts, and forms and functions of representations they would use to engage learners. It is anticipated that, through an in-depth study of the possible cognition of individual students, the results would inform teachers and researchers how students might go about reading and associating diagrams that represented complicated ideas, which is a step forward to delineating challenges students might face in learning from multiple diagrams as a form of representation.

Methodology

Case study was adopted in this study so as to gain an in-depth understanding of students' interpretation of diagrams. Three Grade 10 students, who represented high, medium, and low achievement in biology from a typical secondary school in Hong Kong, were interviewed within a week after they had been taught the topic human circulatory system. The first author attended the lessons when the students learnt the topic. This checked and ensured that the topic was covered and that the diagrams used in the interviews were discussed in the lessons. During the interviews, students' mental visualization was probed into through their oral responses, reading of diagrams, and drawing. The interview protocol was developed based on dual coding theory such that students' mental verbal representations, visual representations as well as the connections between different mental representations could be probed into. In general, each student was asked the followings:

(1) Trace the route of blood from the right atrium to the fingertip and back to the heart.
    This study did not intend to reiterate what has been reported in the literature about students' understanding of blood circulation. Students' response to this question (through their own drawing) would be compared to how they interpreted diagrams representing double circulation. It is expected that through such a comparison, the way that students visualized blood flow in the human body would be interpreted.

(2) Explain what they saw in Figure 2.[1] Specifically, each student was asked 'what do you see in this diagram?' and 'what do you think this diagram wants to tell you?'. Also, they were asked how they interpreted in parts of the diagram where there was void of blood vessels (e.g. at the top of the head). The question is not trivial because it relates to how students interpret those that are not represented in the diagram. Also, an understanding of how arteries and veins are connected (through arterioles, capillaries in body organs and venules) is essential in the understanding of the functioning of the human circulatory system. This task probed into the way students visualized elements that were not represented in a diagram and how vessels were connected in a human body.

(3) Explain what they saw in Figure 3. It probed students' visualization of the relationship between blood vessels.

(4) Explain the relationship between Figure 2, Figure 3 and his/her drawing. This probed into student's visualization of the circulatory system as an integrated system. The student was asked, 'what do you think are the relationships between Figure 2 and Figure 3?' Specifically, the student was asked to indicate in Figure 2 the vessels as represented in the blood flow diagram (Figure 3). Although the blood flow diagram represented the muscular wall thickness of the artery, vein and capillaries through spatial isomorphism, the way the vessels are arranged spatially in the diagram did not specifically refer to a particular part of the body. Also, the label 'an organ' is a general (or abstract) concept. In other words, the diagram used conventions, particularly arrows to represent blood flow. Where appropriate, the students were asked to draw out and explain their ideas about the relationships between the diagrams presented to them.

The interview protocol was developed based on dual coding theory. Students were asked not only to explain verbally or to draw out what they thought. They were asked to explain their drawing as they drew diagrams. It would allow us to probe into their mental verbal representations, mental visual representations and the referential connection between them. Also, they were asked not only to interpret individual textbook diagrams that they came across in their classroom learning, they were asked to point out relationships between relevant diagrams. Where appropriate, they were asked to draw diagrams to represent their association of different diagrams. It allowed us to probe into their mental visual representations and the associative connections across different diagrams. In this study, students' reading of diagrams and their drawing played a significant role in probing into students' visualization. Such a strategy has been shown to reveal students' understanding of ideas that were otherwise very difficult to tap into (Cheng & Gilbert, 2014). In short, especially as far as representing spatial information is concerned, a word or a string of words is a general description, a diagram concretizes such a description. In this study, we expected that drawing could reveal students' visualization of ideas that entailed spatial exactness.

During the interviews, we set up a camera directly above the bench where the interviews were conducted. The setting captured students' pointing of diagrams and their drawing process. The interview videos were then transcribed multimodally (Erickson, 2006). That is, the transcript included both verbal transcript and its corresponding screen shots. An oval or some arrows were added to the screen shots to represent the area under discussion or the gesture a student made over a diagram. Moreover, scans of all students' drawings were included in the transcript to enhance readability.

The biology teacher selected one female (Cyrus) and two male students (Colin and Calvin—all pseudonyms) for the interviews. They represented the low-, middle-, and high-achievement students respectively. Each of the interviews lasted from 25 to 30 minutes. The next section presents data and their interpretation. Through their spoken response and their drawing, we interpreted how they might visualize (i) spatial isomorphic features and conventions of diagrams, and (ii) the structures and behaviours of biological components in achieving their functions.

Results and Interpretation: Cyrus

Focusing on Structural Features

The student responded as follows about her understanding of the diagram (Figure Block A):

> Er, first, the wall of the artery is thicker (while pointing to the red tube and then whirling over the wall vessel, see Figure 4).
> The vein is thinner (while whirling over the wall vessel of the blue tube, see Figure 5).
> Um, the capillaries (Figure 6) contain oxygenated blood and deoxygenated blood.

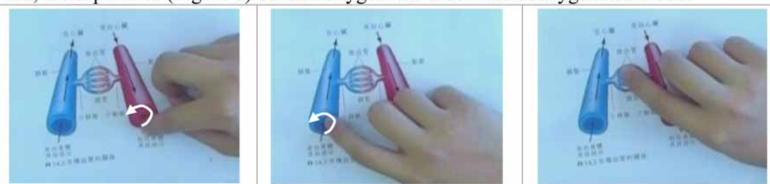


Figure 4 Figure 5 Figure 6

Figure Block A. Cyrus' reading of the blood flow diagram

Cyrus focused only on structural components and composition of the diagrams. These features were represented by the use of spatial isomorphism in the diagram. That is, the arterial wall is thicker than the venous wall. Although the student was able to recognize the convention (represented by different colours) that represented oxygenated and deoxygenated blood, the convention of blood flow (represented by arrows) was not mentioned. The deeper meaning of the diagram in representing the blood flow in the human body was not mentioned.

Cyrus' responses in another task may further support the above interpretation that she did not visualize the blood flow in the diagram. In the discussion of the relationships between the blood flow diagram and the system diagram, she indicated, 'yes, but the capillaries (same pointing as in Figure 6) may not be so clearly shown'. She elaborated the two diagrams as follows (Figure Block B):

> The artery (Figure 7) will follow the red lines to flow (while tracing the red line on the system diagram, see arrow on Figure 8). And the blue follows the blue vessels (see her pointing in Figure 9).

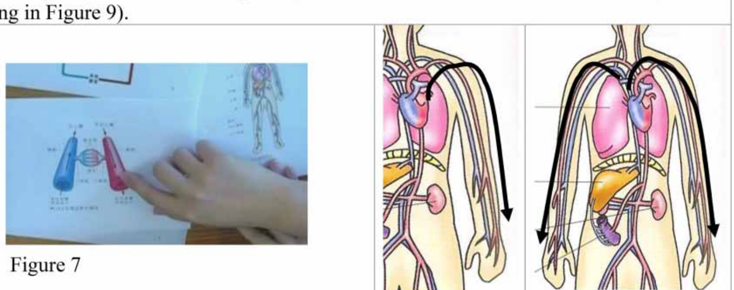


Figure 7 Figure 8 Figure 9

Figure Block B. Cyrus' association of the blood flow diagram and the system diagram

In her responses, Cyrus associated the artery and the vein in Figure 7 with an artery in the arm of Figure 8 and the two veins in Figure 9 respectively. While the mapping was accurate, she seemed to be tracing the *structures* (arteries and veins) rather than then flow of blood (the *behaviour*). Such an interpretation can be supported by her tracing of veins in Figure 9 from the heart to the fingertips. The direction was opposite the blood flow from the veins to the heart in human body and that represented in the blood flow diagram. It is likely the student did not visualize the message in the blood flow diagram that the blood went from the artery to the capillaries, then to the veins and finally back to the heart. Cyrus likely only visualized the structural features of the diagram. The same focus was evident when she interpreted both the blood flow diagram and the system diagram. The blood flow (behaviour) was not visualized.

Results and Interpretation: Colin

Visualizing Structures and Behaviours

Colin, the medium-achieving student, responded as follows when he was asked his interpretation of the diagram (Figure Block C):

I can see the arteriole, artery, vein and capillaries.... It wants to say that the blood comes from the heart. It flows through the artery (while moving his finger along the artery, as indicated in Figure 10), some of them go to other parts of the body. Some flow through the arteriole (while pointing at the junction of the artery and the arteriole see Figure 11) to the capillaries.

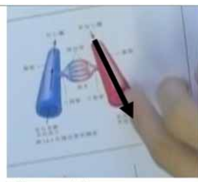


Figure 10

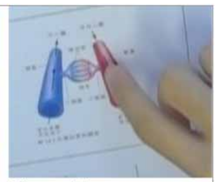


Figure 11

The capillaries go to other organs. They undergo-, they supply oxygen to the organs. Then, the blood becomes deoxygenated blood. It passes through the venules, and then back to the vein and then to the heart.

Figure Block C. Colin' reading of the blood flow diagram

Colin started by naming the *structures* of the diagram. He also seemed to have visualized the process through which the blood went from the heart via different types of blood vessels and back to the heart (*behaviour*), and a *function* of the capillaries, that is, to 'supply oxygen to the organs'.

It may be argued that the annotations and arrows in the diagram have provided all the hints required for students' reading. We believe that although there were arrows indicating the direction of blood flow in the artery and the vein, there was no arrow indicating that the arterial blood branched out and went to the arteriole, etc. It was Colin who filled in the missing arrows, that is, the blood went from the artery, to the arteriole (Figure 11), capillaries/organs, venule, and then to the vein. Therefore, he did not merely verbalize what was shown in the diagram. He likely associated his own mental visual or verbal representations of blood flow with the diagram in a scientific sense.

Applying Spatial Features on Conventions

Colin was able to visualize the generalized idea of blood flow in different blood vessels that was not attached to a particular part of the human body. When he was asked the relationship between the blood flow diagram and the system diagram (which were put side by side in front of him), he drew a circle in the system diagram and explained the following (Figure Block D):

It is because the vein and artery are here (while referring to the circle in Figure 12). And next to them there are kidney and liver. It can-, the capillaries can go to the organs.

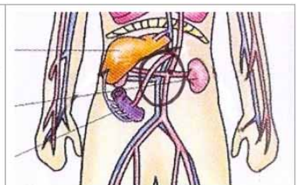


Figure 12

Figure Block D. Colin' association of the blood flow diagram and the system diagram

By his circling and the oral response, it seems that Colin associated the two diagrams by means of their structural features, namely the parallel running artery and vein in both diagrams. Although he mentioned kidneys and liver, and that 'capillaries can go to the organs', he did not address how the blood flowed from an artery to an organ and then to a vein. Also, it is worth noting that his circling did not include any organs. Therefore, the way he might visualize the blood flow across different blood vessels and body organs in the system diagram was not certain. Nevertheless, Colin' subsequent drawing might be revealing (Figure Block E):

(Right after he drew the diagram in Figure 13, he started explaining.) These capillaries.
They go to the organ (while drawing a kidney, see Figure 14).
Then they come out (Figure 15), and go back to the vein (Figure 16).

Figure 13

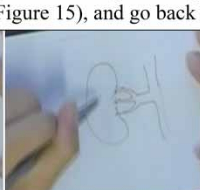


Figure 14

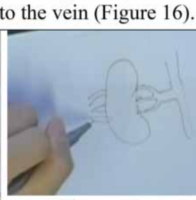


Figure 15

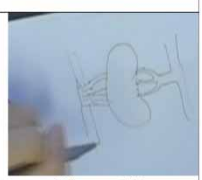


Figure 16

Figure Block E. Colin' drawing of relationship between blood vessels and the kidney

The drawing possessed an artery, an arteriole (not spoken in the interview), capillaries, the kidney, and a vein. The spatial orientation of the blood flow diagram and his drawing was identical. That is, the blood went into the organ from the right-hand side and went out of the organ in the left-hand side. Different conventions could have been employed to represent the direction of the blood flow, such as from left to right, which is the orientation when writing. It might also be the same as that in the human body, in which renal arteries and veins bring blood to and away from the kidney at the same side of the organ. Therefore, it is likely that the drawing was based on the blood flow diagram.

An intriguing observation from Colin's drawing is that instead of having capillaries ***embedded*** in the organ, he might have visualized that the capillaries ***went into*** the organ from the outside, and then the blood ***went out*** of the organ to capillaries. The focus here is not the student's 'misconceptions'[2] or that the student did not grasp the spatial location of capillaries, but to suggest how Colin might have interpreted the relationship between the system diagram and the blood flow diagram, and how he came up with this drawing.

It is likely that he added spatial isomorphic features (i.e. a kidney) to the blood flow diagram that represented blood flow through conventions. The process of his drawing and his explanation (Figure Block E) was a transformation of the blood flow diagram into his own drawing. The main difference between the diagram and his drawing was that while the diagram used conventions heavily and was a generalized representation, the student seemed to make his drawing a specific instance of blood flow into and away from the kidney. His drawing had a higher spatial isomorphism, evident in the drawing of the kidney. In other words, he might have interpreted the high-convention blood flow diagram as if it was spatially isomorphic to the human body. The system diagram was interpreted in the light of the blood flow diagram. The process is represented in Figure 17.

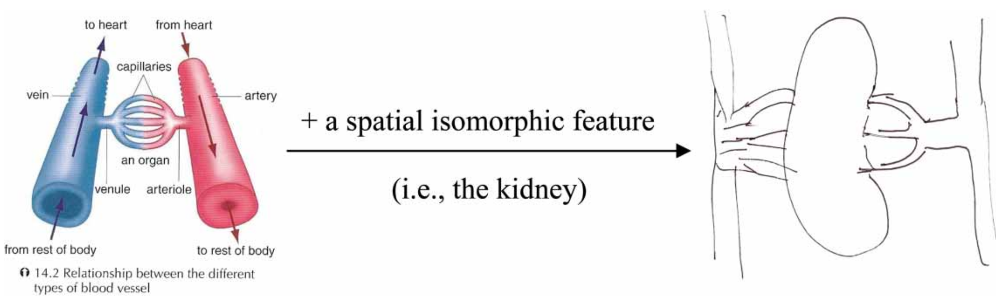


Figure 17. Colin's association of the blood flow diagram and the system diagram

Colin's drawing revealed his visualization of the spatial relationship between the *structure* of capillaries and a body organ. By merely referring to his oral interpretation of the blood flow diagram in Figure Block C, as the student stated, 'the capillaries go to other organs', this could seem unproblematic. However, when the same verbal representation is mapped into his drawing (Figure 16), the verbal phrase could have meant two things:

(a) The capillaries were outside the organ. Hence, the blood went to the capillaries from the arteriole, and then to the organ.

(b) The capillaries were embedded inside the organ. The blood went to the capillaries, hence, the organs.

Only (b) is the accepted scientific idea, whereas (a) is inaccurate in terms of the spatial relationship between the structure of capillaries and the organ. More importantly, (a) violates the function of capillaries, which is to facilitate exchanges of materials between the blood and body organs. Although the two meanings are rather different, both can be encapsulated in the statement '[the] capillaries go to other organs'. The way Colin mentally visualized the relationship between an organ and capillaries could not have been revealed if he had not been asked to draw his idea.

Colin seemed to have visualized the blood flow (behaviour) in the blood flow diagram when it was stand-alone, and had verbalized the functional aspect of the blood flow. Nevertheless, the making of associative connections between the blood flow diagram and the system diagram (with a high spatial isomorphism) was challenging. Although he could verbally state the *functions* and the *behaviours* of blood circulation, these functions and behaviours were not supported by his mental visual representation of the *structural connection* of blood vessels and the kidney. The case study demonstrated a way Colin associated diagrams. He seemed to have identified similar structural features of the two diagrams (i.e. the parallel artery/vein pair) to start with. Some spatial isomorphic features (i.e. a kidney in the system diagram) were added to the blood flow diagram despite the fact that the parallel running of an artery and a vein was not necessarily spatial isomorphic to the human body.

Results and Interpretation: Calvin

Mapping Spatial Features of Diagrams

In various parts of the interview, Calvin has demonstrated his capability in visualizing the double circulatory system. He was able to respond orally and by drawing how blood circulated in the pulmonary and systemic circulations. For example, his interpretation of the blood flow diagram was as follows:

> ... how blood flows from artery to vein ... That is, from the artery, through the arteriole, to the capillaries, return to venule, to the vein, then back to the heart.

The data showed that Calvin did not focus on the spatial features of the diagram only (such as the thickness of the artery and vein walls). He visualized the *structures* in relation to the *behaviour*, that is, the flow of blood from the artery to the vein and back to the heart. As discussed earlier, the diagram did not provide all the information that was required for the visualization of the blood flow. It is likely that Calvin was able to visualize the blood flow in the diagram.

When Calvin was asked the relationship between the blood flow diagram and the system diagram, he circled a pair, an artery and a vein, in the right leg, and explained the followings (Figure Block F):

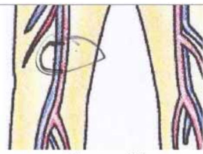
 Figure 18	Um, left (referring to the blue part in Figure 18) is the vein, right (referring to the red part in Figure 18) is the artery.

Figure Block F. Calvin's drawing of relationship between blood vessels and the kidney

In other words, although he was able to visualize the blood flow when the blood flow diagram was stand-alone, he seemed to have used its spatial feature, that is, the parallel artery, and vein as a lens to visualize the system diagram.

The purpose of this study was to identify some ways that students might possibly associate diagrams during their learning, rather than to report students' misconceptions. In another episode of the interview, Calvin indeed demonstrated his visualization of blood flow from the system diagram. After he pointed out that the red vessels represented arteries and the blue vessels represented veins (in Figure Block G), the interaction was as follows:

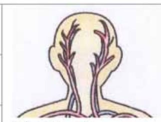
I	Ok, then in the head, there is an artery flow to the head (pointing at the head of Figure 2, highlighted in Figure 19), and then it disappears.	 Figure 19
S	Because these are capillaries, I think they are too small, so they are simplified, not shown in here.	
I	Ok, then, after the capillaries, where will the blood go?	
S	Er, it's used by the cells. When the nutrients are used up, it goes back to the vein, that means the blue one, then goes back to heart.	

Figure Block G. Calvin's reading of blood flow in the system diagram

This interview excerpt demonstrated that Calvin was able to visualize the blood flow from the arteries to brain, via capillaries, back to the veins and then the heart. The associative connection between the diagram and his mental representation of the relationship between different types of blood vessels was scientific. In the area where there were no arteries or veins, he was capable of 'filling in' the empty space with capillaries. In addition, he did not only visualize the *structure* (i.e. blood vessels) and the pathway (i.e. the *behaviour* of the blood flow), but he also related them to their *function* ('used by the cells . . . the nutrients are used up . . . '); that is, the blood transported nutrients to the cells where the capillaries passed through.

The above discussion aimed to provide evidence that Calvin could visualize scientifically the blood flow represented in the system diagram. It suggests that his responses as reported in Figure Block F should not be taken as merely a misinterpretation of the system diagram. Rather, it revealed a way that the student might have associated diagrams. That is, spatial isomorphic components of diagrams, rather than meaning embedded in conventions, were taken as features for the mapping. In this case, the parallel running of an artery and a vein in the blood flow diagram was mapped to the artery and the vein in the system diagram.

Discussion

This paper presented data of three interviews. The data collection was guided by dual coding theory, which emphasizes the role of connections between verbal–visual representations and visual–visual representations. Making these connections is essential in learning science. The data presented here focused on some ways that the students mentally visualized diagrams and how they associated different diagrams that represented various aspects of the human circulatory system. Spatial isomorphism and the use of conventions relate diagrams to their referents. This idea was not only useful in shedding light on the nature of diagrammatic representations; it also helped us to conceptualize some ways that the students interpreted diagrams. In this section, we discuss generally the data drawn from the three cases regarding students' visualization of the blood flow diagram and their association of the diagram with the system diagram.

Reading the Spatial Isomorphic Features vs. the Conventions

Calvin and Colin visualized the blood flow across different blood vessels in Figure 3. It was consistent with the conventions used in the diagram, in which some arrows were attached to the artery and the vein. The diagram/arrows did not represent the complete route of the blood flow. For example, the way the blood went from the artery to the vein was not represented. It was only through the readers' interpretation, which was based on their existing mental representations of blood flow, that such a route could be visualized. Therefore, their visualization could not be rote reading from the diagram. Calvin and Colin did visualize the blood flow (as *behaviour*) embedded in the diagram, which used the convention in representing the blood flow. They were able to suggest some *functions* of the system.

Instead of using the convention to guide her reading, Cyrus focused on the spatial isomorphic features of the diagram, namely the vascular wall of the artery being thicker than that of the vein. She only visualized the *structural* features. Meanwhile, the blood flow across different vessels (*behaviour*) and the *functional* significance of the differential thickness were not touched upon. Her pointing to blood vessels in the system diagram gave support to the interpretation that her visualization of blood flow (*behaviour*) in different blood vessels was an issue.

A comparison of the data of the three students revealed an important issue about students' visualization of the diagram that represented through conventions. While some students could identify messages represented through conventions, some students—possibly those regarded as low achieving in biology—could focus on only the spatial features or structural components. Although the reading of the *spatial/structural* components could be accurate, it could miss the idea of blood flow (*behaviour*) as an important message of the diagram. The findings were in general consistent with earlier studies (Hmelo-Silver et al., 2007). Calvin, the highest achiever, demonstrated an integrated understanding of the SBF of the system. Cyrus, the lowest achiever, visualized only the structures. While Colin referred to the SBF of the system, it was questionable if his mental visual representation of the structures could support functions of the system.

Reading the Verbal Caption

The title of the blood flow diagram stated 'Relationship between the different types of blood vessel'. Such a verbal statement might have led to multiple interpretations by the students. In terms of a *structural* relationship, the caption might be taken as a comparison of the thickness of the wall of different vessels. It was represented by the cross-sectional view of the artery and the vein, and by spatial isomorphism. In terms of blood flow (*behaviour*), the caption could mean the sequence through which the blood flows through different types of blood vessels. Calvin and Colin might have related the verbal caption to the blood flow (represented by convention); Cyrus might have related to the different thicknesses of the blood vessels (represented by their spatial isomorphic features in the diagram). We argue that all three students were indeed accurate in associating the diagram and its caption—only that the linkages were different.

The issues at stake are not only about multiple interpretations of a diagram, but also multiple accurate linkages of the caption and the diagram. Students focusing on the spatial features and *structural* components of the diagram could lead to one interpretation; those focusing on the convention and the blood flow (*behaviour*) could lead to a deeper interpretation.

Relating the Blood Flow Diagram and the System Diagram

Given the differences in ways the students interpreted the blood flow diagram, perhaps not surprisingly, their ways of associating the diagram with the system diagram were also different.

With a focus on the spatial features of the blood vessels in the blood flow diagram, Cyrus referred to the arteries and veins and commented on the absence of capillaries in the system diagram. She made no reference to the blood flow in the gross structure. It was consistent with her visualization of the blood flow diagram. In short, in her visualization of the two diagrams, spatial isomorphic features were the main focus, which resulted in her discussion of the *structures,* but not the *functions* or *behaviours* of the biological structures.

Although Colin visualized the process of the blood flow represented by conventions in the blood flow diagram, he quite strictly applied its spatial features, namely the vertical and parallel running of the artery–vein pair and the capillaries perpendicular to the artery–vein pair, in his interpretation of the system diagram. An organ was added to the space between the capillaries in his drawing (Figure 17). This supports our interpretation that he might have taken the spatial features of the blood flow diagram literally. Another important issue was his visual representation of his verbal statement 'the capillaries go to other organs'. Although the verbal statement did not seem to be problematic, further probing by drawing revealed that the capillaries went into the kidney from the outside of the organ. The finding suggested that Colin's mental visual representation of the structural relationship of capillaries and kidneys might have been mediated by his verbal recall of the sequence 'artery, arterioles, capillaries, organs, venules, vein'. That is, Colin might have formed the mental visual representation based on his verbal recall of the above sequence through a referential connection across the mental verbal and visual systems. The drawing suggested that his mental visual representation of the structural relationship between capillaries and the kidney, and the blood flow between them, did not support a scientific understanding of the functional adaptation of capillaries. The interpretation of such excessive reliance on verbal recall is consistent with an earlier study which suggested that some students might have relied on recall in their verbal system when they learnt the structure of metals and the model that used to explain the malleability of metals (Cheng & Gilbert, 2014). Also, the finding reiterates the importance of probing students' ideas through a combination of oral interviews and their own drawing. It is especially important when the students' idea under investigation involves spatial relationship or structures.

In some ways, Calvin's association of the two diagrams was similar to that of Colin. Although he visualized the blood flow (*behaviour*) represented by conventions, Calvin used the spatial features of the blood flow diagram, that is, the parallel running of the artery and the vein (structures), when he mapped the two diagrams. This was supported by his circling of the system diagram and his verbal responses of the relationship between diagrams. In the mapping, the blood flow (*behaviour*) that he addressed in the interpretation of the blood flow diagram was no longer addressed. His focus was on the spatial and *structural* features of the blood vessels in the system diagram, that is, the parallel running of an artery and a vein.

Based on the data, it is argued that structural features represented by spatial isomorphism played a significant role in the students' reading of a diagram even if conventions were used to represent ideas. The spatial features were so important that Cyrus focused mainly on them. Colin and Calvin could visualize the idea of blood flow carried by conventions; however, they applied spatial features of the blood flow diagram when they tried to link it to the system diagram. It is likely that students in general might tend to use spatial features in mapping the diagrams irrespective of their representation through convention usage or spatial isomorphism. The finding is consistent with the literature on students' interpretation of graphs, that is, they could map spatial features of a curve to the real world without considering the convention of graphs in representing the physical world (Leinhardt, Zaslavsky, & Stein, 1990; Sharma, 2006; Testa, Monroy, & Sassi, 2002). This study extends their findings by highlighting the role of spatial features played in students' interpretation and association of diagrams. Even students could visualize the deeper meanings of a diagram represented by conventions. When they were asked to develop associative connections between different diagrams, they may revert to the reliance of structural or spatial features in their mapping.

It has been suggested that symbolism being a hurdle for students' interpretation of diagrams, and that students might tend to focus on 'superficial features' in their reading of diagrams (Anderson, Schönborn, du Plessis, Gupthar, & Hull, 2013). The finding of this study is consistent with earlier studies, in the sense that symbolism can be regarded as the use of 'conventions' in representations. This study specifies that reading of superficial features can be taken as students' literal interpretation of spatial features of components of a diagram, irrespective of whether the components represent through spatial isomorphism or convention. In other words, in some cases, misinterpretation of a diagram because of students' reading of its superficial features can be regarded as students assigning spatial isomorphism to components of a diagram that indeed represent through conventions.

Conclusions and Implications for Teaching and Learning

This study extends what has been reported in the literature about students' understanding of the human circulatory system (Arnaudin & Mintzes, 1985; Assaraf et al., 2013; Pelaez et al., 2005). Existing studies reported students' conceptions of the human double circulation. This study delved into some ways that students visualized diagrams, which revealed how they might have visualized the structural relationship between blood vessels and other body organs, and the blood flow across them.

This study investigated some ways that students visualized and associated diagrams that represented aspects of the human circulation system. Broadly speaking, students seemed to have relied on structural features that represented through spatial isomorphism in associating diagrams. We observed differences across students with different academic achievement. It was found that the lowest achieving student Cyrus focused on structural features of the blood flow diagram. She did not seem to visualize the blood flow that was represented through conventions. The medium-achieving student Colin visualized the structural features and the process of blood flow, and was able to name the function of such a blood flow. Nevertheless, he applied the spatial feature of the blood flow diagram strictly when he visualized the system diagram. It was also found that, although his oral recall of blood flow to organs might seem scientific, his drawing revealed that his mental visual representation of the spatial relationship between capillaries and organs was not scientific. The student might have relied on his verbal system in recalling the structure and blood flow, which resulted in a referential connection that led to a scientifically inaccurate mental visual representation and hence drawing. Calvin, the highest achieving student, demonstrated that he was able to visualize the blood flow in the blood flow diagram and the system diagram. When he was asked to map the two diagrams, he seemed to have relied on spatial features only.

This paper further supports the role of dual coding theory in enhancing our knowledge of some ways that students learn science. Drawing on the nature of diagrammatic representations, namely through the use of conventions and spatial isomorphism, this paper contributes to our knowledge of how students associate different diagrams in their learning. As students learn scientific concepts through multiple diagrams, it is imperative that the ways they deal with them are ascertained.

Implications for Teaching and Learning

Being able to visualize the structure of body organs where capillaries are embedded is important not only in the circulatory system. It is also important for the learning of other biological concepts that involve an exchange of materials between blood in capillaries and tissue fluid between cells, for example, the renal system, respiratory system, and lymphatic system. We are concerned that students who do not visualize the structural relationship between capillaries and body organ or who focus on the structural aspects of diagrams, as indicated by the data of Colin and Cyrus respectively, would have big challenges in learning concepts associated with the exchange of materials in other body systems. In the light of the findings of this study, we would like to suggest the followings in relation to teaching and learning with diagrams:

On the Design of Diagrams

It is important to have a verbal caption to the diagram (Pozzer & Roth, 2003; Pozzer-Ardenghi & Roth, 2005). We believe that merely having a caption that describes the diagram is not sufficient. More specifically, the caption should describe explicitly what is intended for readers. The caption 'relationship between the different types of blood vessel' might have been so unspecific that it would leave readers for open interpretations. In this connection, a consideration of the SBF features that the diagram aims to represent might be a useful guide. The blood flow diagram was visualized as merely a *structural* representation; yet, it actually also represented the *behaviour* of blood flow (or blood flow as a process) in different blood vessels and organs. Given the difficulties students might face in their learning from structure to process (Chi, 2008), it is important that diagram designers or textbook authors would make it explicit that the diagram aims to represent such a process. We envisage that the caption 'blood flow in different blood vessels' might better reflect the diagrammatic representation and facilitate students in constructing a deeper understanding of the diagram (Ainsworth, 2008).

Arrows have been known to help communicating dynamic processes, and students have been found to be able to use arrows to represent dynamic process in their drawings (Akaygun & Jones, 2014; Heiser & Tversky, 2006). In order to make the dynamic process of blood flow (or as a behaviour) more explicit, it is suggested that the diagram may include arrows pointing from the artery to the arteriole and from the venule to the vein. Although Calvin and Colin were able to visualize the blood flow even when some arrows were missing, it is likely that such an explicit symbol can guide students like Cyrus who might not have visualized the process/behaviour of blood flow.

On Teaching with Diagrams

This study revealed that students' mental visual representations of structural relationship between blood vessels and body organs could be unscientific irrespective of the seemingly accurate verbal description. It lends support to the role that multiple representations—the verbal mode and the visual mode as argued in this study—should play in teaching and learning (Treagust & Tsui, 2013). Dual coding theory suggests that information processing is more efficient when both the mental verbal and visual systems are made use of. We agree with Roth and Pozzer-Ardenghi (2013) that students have to learn to read diagrams through social interactions. An implication of dual coding theory is that verbalizing diagrams and concretizing general verbal statements by drawing would facilitate learning (Paivio, 2007). In this connection, teachers could create opportunities for students to verbalize their ideas both on a given diagram(s). Students could be engaged in classroom talk of their interpretation of diagrams, such as the blood flow diagram and/or the system diagram. Similarly, where appropriate, students should be encouraged to use drawing to represent their understanding of scientific ideas (Tytler et al., 2013), such as how the circulatory system facilitates the exchange of materials in organs such as the kidneys. The drawing could form the basis through which teachers assess students' understanding. Nevertheless, little is reported in the literature about how teachers should best utilize textbook diagrams in their classroom teaching. More research studies should be conducted to inform science teachers what good practice should be like in this area (Liu et al., 2014).

In biology textbooks, diagrams are used to support the representations of ideas. There is little evidence that teachers help students to understand diagrams, that is to say, to help students to develop an integrated understanding based on different diagrams (Eilam, 2012). This study reveals that students might have relied on similarities of spatial features in associating diagrams. In this connection, students should be facilitated to understand relationship between different diagrams, and how different diagrams would contribute to an integrated idea of a biological system. It is suggested that science education researchers could explore how best to support students' learning with diagrams in classroom environments.

On Teaching about Diagrams

A diagram can be taken as a representation of its referent. It is thus analogical in nature. A diagram represents its referent is by spatial isomorphism and by convention. It seems that, as this study shows, mapping of spatial isomorphic features of a diagram with their referents (e.g. an artery with a thicker vascular wall) is less problematic. Problems might arise when readers of a diagram focus on the spatial features of a convention and ignore the deeper meaning represented by the convention. Results of other studies on students' (mis)understanding of diagrams also revealed that some students might have taken the spatial features of conventions literally. Thus, it may be worthwhile for teachers to discuss with students some features of diagrammatic representations. When teaching about diagrams, teachers may discuss the parts of a diagram that resemble its referents, the parts of a diagram that should not be taken as resembling its referents, and the meaning carried by those parts. Specifically, in the teaching of the blood flow diagram, teachers might like to help students to understand that the parallel running of the artery and the vein does not necessarily replicate the way the vessels locate in human bodies (but merely as a way to represent the blood flow more clearly). Also, students should learn how the ideas represented in the diagram associate with the blood flow in human body or body organs.

Notes

1. In Hong Kong, some schools use Chinese language as the medium of instruction; other schools use English. Therefore, there are two versions of the same set of textbooks in the market. Their contents are equivalent; only that, one is in Chinese language, and the other is in English. This diagram was obtained from the English version of the textbook that students used. The first author has checked that the annotations and the captions to the diagrams in both Chinese and English versions have equivalent meanings.
2. Biologically, the function of capillaries is to facilitate exchanges of materials. Based on the drawing, the student seemed to have missed an important structural–functional relationship of capillaries. However, the discussion here will not go into the 'misconception' the student might have.

References

Ainsworth, S. (2008). The educational value of multiple-representations when learning complex scientific concepts. In J. K. Gilbert, M. Reiner, & M. Nakhleh (Eds.), *Visualization: Theory and practice in science education* (pp. 191–208). Dordrecht: Springer.

Ainsworth, S., & Loizou, A. T. (2003). The effects of self-explaining when learning with text or diagrams. *Cognitive Science*, *27*(4), 669–681.

Akaygun, S., & Jones, L. L. (2014). Words or pictures: A comparison of written and pictorial explanations of physical and chemical equilibria. *International Journal of Science Education*, *36*(5), 783–807.

Anderson, T. R., Schönborn, K. J., du Plessis, L., Gupthar, A. S., & Hull, T. L. (2013). Identifying and developing students' ability to reason with concepts and representations in biology. In D. F. Treagust & C.-Y. Tsui (Eds.), *Multiple representations in biological education* (pp. 19–38). Dordrecht: Springer.

Arnaudin, M. W., & Mintzes, J. J. (1985). Students' alternative conceptions of the human circulatory system: A cross-age study. *Science Education*, *69*(5), 721–733.

Assaraf, O. B.-Z., Dodick, J., & Tripto, J. (2013). High school students' understanding of the human body system. *Research in Science Education*, *43*(1), 33–56.

Bertin, J. (2011). *Semiology of graphics: Diagrams, networks, maps*. Redlands, CA: Economic & Social Research Institute Press.

Chan, W. K., Chu, S. F., & Kwong, S. W. (2006). *New biology: A modern approach* (Vol. *2*). Hong Kong: Aristo.

Cheng, M. M. W., & Gilbert, J. K. (2014). Students' visualization of metallic bonding and the malleability of metals. *International Journal of Science Education*, *36*(8), 1373–1407.

Cheng, P. C.-H. (1996). Functional roles for the cognitive analysis of diagrams in problem solving. In G. W. Cottrell (Ed.), *Proceeding of the eighteenth annual conference of the cognitive science society* (pp. 207–212). Hillsdale, NJ: Lawrence Erlbaum.

Chi, M. T. H. (2008). Three types of conceptual change: Belief revision, mental model transformation and categorical shift. In S. Vosniadou (Ed.), *International handbook of research on conceptual change* (pp. 61–82). New York, NY: Routledge.

Chi, M. T. H., De Leeuwa, N., Chiu, M.-H., & Lavancher, C. (1994). Eliciting self-explanations improves understanding. *Cognitive Science*, *18*(3), 439–477.

Cook, M., Carter, G., & Wiebe, E. N. (2007). The interpretation of cellular transport graphics by students with low and high prior knowledge. *International Journal of Science Education*, *30*(2), 1–23.

diSessa, A. A., Hammer, D., Sherin, B., & Kolpakowski, T. (1991). Inventing graphing: Meta-representational expertise in children. *Journal of Mathematical Behavior*, *10*(2), 117–160.

Eilam, B. (2012). *Teaching, learning, and visual literacy: The dual role of visual representation*. New York: Cambridge University Press.

Erickson, F. (2006). Definition and analysis of data from videotape: Some research procedures and their rationales. In J. L. Green, G. Camilli, & P. B. Elmore (Eds.), *Handbook of complementary methods in education research* (pp. 177–191). Mahwah, NJ: Lawrence Erlbaum Associates; Washington, DC: American Educational Research Association.

Hegarty, M. (2004). Diagrams in the mind and in the world: Relations between internal and external visualizations. In A. Blackwell, K. Mariott, & A. Shimojima (Eds.), *Diagrammatic representation and inference* (pp. 1–13). Berlin: Springer-Verlag.

Hegarty, M. (2011). The cognitive science of visual-spatial displays: Implications for design. *Topics in Cognitive Science*, *3*(3), 446–474.

Hegarty, M., Carpenter, P. A., & Just, M. A. (1991). Diagrams in the comprehension of scientific texts. In R. Barr, M. L. Kamil, P. Mosenthal, & P. D. Pearson (Eds.), *Handbook of reading research* (Vol. *2*, pp. 641–668). New York, NY: Longman.

Heiser, J., & Tversky, B. (2006). Arrows in comprehending and producing mechanical diagrams. *Cognitive Science*, *30*(3), 581–592.

Hmelo-Silver, C. E., Marathe, S., & Liu, L. (2007). Fish swim, rocks sit, and lungs breathe: Expert-novice understanding of complex systems. *The Journal of the Learning Sciences*, *16*(3), 307–331.

Larkin, J. H., & Simon, H. A. (1987). Why a diagram is (sometimes) worth ten thousand words. *Cognitive Science*, *11*(1), 65–100.

Leinhardt, G., Zaslavsky, O., & Stein, M. K. (1990). Functions, graphs, and graphing: Tasks, learning, and teaching. *Review of Educational Research*, *60*(1), 1–64.

Liu, Y., Won, M., & Treagust, D. F. (2014). Secondary biology teachers' use of different types of diagrams for different purposes. In B. Eilam & J. K. Gilbert (Eds.), *Science teachers' use of visual representations* (pp. 103–121). Dordrecht: Springer Science + Business Media B.V.

Lohse, G. L., Biolsi, K., Walker, N., & Rueter, H. H. (1994). A classification of visual representations. *Communications of the ACM archive*, *37*(12), 36–49.

Mayer, R. E. (2009). *Multimedia learning* (2nd ed.). Cambridge: Cambridge University Press.

Novick, L. R., & Catley, K. M. (2014). When relationships depicted diagrammatically conflict with prior knowledge: An investigation of students' interpretations of evolutionary trees. *Science Education*, *98*(2), 269–304.

Paivio, A. (1986). *Mental representations: A dual coding approach*. New York, NY: Oxford University Press.

Paivio, A. (2007). *Mind and its evolution: A dual coding theoretical approach*. Mahwah, NJ: Lawrence Erlbaum Associates.

Pelaez, N. J., Boyd, D. D., Rojas, J. B., & Hoover, M. (2005). Prevalence of blood circulation misconceptions among prospective elementary teachers. *Advances in Physiology Education*, *29*(3), 172–181.

Pozzer, L. L., & Roth, W.-M. (2003). Prevalence, function, and structure of photographs in high school biology textbooks. *Journal of Research in Science Teaching*, *40*(10), 1089–1114.

Pozzer-Ardenghi, L., & Roth, W.-M. (2005). Making sense of photographs. *Science Education*, *89*(2), 219–241.

Roth, W.-M., & Pozzer-Ardenghi, L. (2013). Pictures in biology education. In D. F. Treagust & C.-Y. Tsui (Eds.), *Multiple representations in biological education* (pp. 39–53). Dordrecht: Springer.

Scaife, M., & Rogers, Y. (1996). External cognition: How do graphical representations work? *International Journal of Human-Computer Studies*, *45*(2), 185–213.

Schnotz, W. (2005). An integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 49–69). Cambridge: Cambridge University Press.

Schönborn, K. J., & Anderson, T. R. (2009). A model of factors determining students' ability to interpret external representations in biochemistry. *International Journal of Science Education*, *31*(2), 193–232.

Sharma, S. V. (2006). High school students interpreting tables and graphs: Implications for research. *International Journal of Science and Mathematics Education*, *4*(2), 241–268.

Sungur, S., & Tekkaya, C. (2003). Students' achievement in human circulatory system unit: The effect of reasoning ability and gender. *Journal of Science Education and Technology*, *12*(1), 59–64.

Taber, K. S. (2014). *Modelling learners and learning in science education*. Dordrecht: Springer.

Testa, I., Monroy, G., & Sassi, E. (2002). Students' reading images in kinematics: The case of real-time graphs. *International Journal of Science Education*, *24*(3), 235–256.

Treagust, D. F., & Tsui, C.-Y. (Eds.). (2013). *Multiple representations in biological education*. Dordrecht: Springer.

Tytler, R., Prain, V., Hubber, P., & Waldrip, B. (Eds.). (2013). *Constructing representations to learn in science*. Rotterdam: Sense Publishers.

Viennot, L., & Kaminski, W. (2006). Can we evaluate the impact of a critical detail? The role of a type of diagram in understanding optical imaging. *International Journal of Science Education*, *28*(15), 1867–1885.

Waldrip, B., & Prain, V. (2013). Teachers' initial response to a representational focus. In R. Tytler, V. Prain, P. Hubber, & B. Waldrip (Eds.), *Constructing representations to learn in science* (pp. 15–30). Rotterdam: Sense Publishers.

Won, M., Yoon, H., & Treagust, D. F. (2014). Students' learning strategies with multiple representations: Explanations of the human breathing mechanism. *Science Education*, *98*(5), 840–866.