A Picture is Worth a Thousand Words: A Cross-curricular Approach to Learning about Visuals in STEM

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Abstract: *Visuals are a central feature of STEM in all levels of education and many areas of employment. The wide variety of visuals that students are expected to master in STEM prevents an approach that aims to teach students about every type of visual that they may encounter. This paper proposes a pedagogy that can be applied across year levels and learning areas, allowing a school-wide, cross-curricular, approach to teaching about visual, that enhances learning in STEM and all other learning areas. Visuals are classified into six categories based on their properties, unlike traditional methods that classify visuals according to purpose. As visuals in the same category share common properties, students are able to transfer their knowledge from the familiar to unfamiliar in each category. The paper details the classification and proposes some strategies that can be can be incorporated into existing methods of teaching students about visuals in all learning areas. The approach may also assist students to see the connections between the different learning areas within and outside STEM.*

Keywords: visuals, visual literacy, pedagogy, STEM

1. Introduction

Visual representations, or visuals, such as diagrams, illustrations, photographs, scale drawings, maps, charts, figures, icons, graphs, plots, networks, sketches, animations, and plans are a central feature of the sciences, technology, engineering and mathematics (STEM). They are a key part of these learning areas in school and extend into post-school education and training, and many areas of employment.

Table 1. NAPLAN questions that include visuals.

Year	2008		2009		2010		2011		2012	
Test	Visuals	Ques-tions	Visuals	Ques-tions	Visuals	Quest-ions	Visuals	Ques-tions	Visuals	Ques-tions
Yr 3	30	35	22	35	29	35	21	35	23	35
Yr 5	34	40	22	40	31	40	23	40	24	40
Yr 7 Non-calc	21	32	20	32	18	32	19	32	15	31
Yr 7 Calc	19	32	16	32	22	32	16	32	17	32
Yr 9 Non-calc	21	32	11	31	20	32	13	32	11	32
Yr 9 Calc	17	32	14	31	24	32	19	32	16	32

Perusal of most school mathematics and science textbooks reveals that visual images appear on almost every page. Assessment items also make extensive use of visual images. For example, Table 1 shows the extent of visuals in the National Assessment Program Literacy and Numeracy (NAPLAN) standardized numeracy tests undertaken by all Australian students in Years 3, 5, 7, and 9 (ACARA, 2009, 2010, 2011, 2012; Ministerial Council for Education Early Childhood Development and Youth Affairs, 2008). The increasing availability in schools of software that assist in the production of visuals provides more opportunities for students to create their own visual images.

Reading is no longer limited to processing information in words. In 1994, Moore and Dwyer suggested that visuals may be the main source of modern communication and information. Unsworth and Chan (2009) observed that visuals are increasingly used to complement the use of words to convey meaning. This leads to the concept of visual literacy, defined by Avgerinou and Petterson (2011) as the ability to read and interpret visual statements (decoding), write and create visual statements (encoding), and think visually. It involves cognitive functions such as making meaning, imaging, visualizing, inferring, critical viewing and thinking, as well as communicating and evoking feelings and attitudes. Visual literacy must be learned, drawing on prior experience and context.

The expectation that students can use visual images successfully may be more demanding than many teachers realise. Evaluation of these skills against Bloom's taxonomy (Anderson et al., 2001) shows that they involve the higher order thinking processes of analysing, evaluating and creating. Lowrie and Diezmann (2005) confirmed that decoding and encoding visuals is challenging for some students. The extent of the challenge is influenced by the student's age and the relative difficulty of the visual image. Baker, Corbett, and Koedinger (2001) reported that students are not necessarily able to correctly transfer knowledge about one type of graph (bar graphs) to other informationally equivalent visuals (scatterplots and stem and leaf plots). It is suggested that this is partly due to the wide variety of visuals that students are likely to encounter. The extent of this variety makes it difficult for teachers to expose students to every possibility. It follows that an approach which aims to teach students about every variation of each type of visual likely to be encountered in STEM is neither practical nor likely to be successful.

Wall and Benson (2009) supported this view, stating that "focussing on the big ideas or concepts that graphs have in common is more useful and less time-consuming than studying many individual graphs" (p. 84). They proposed a five-fold classification of the various graphs, arguing that "by teaching students the features of these categories and using different types of graphs as examples, students will be better prepared to read and understand both traditional and new graphs" (p. 84). However, the Wall and Benson classification was confined to the display of quantitative information in mathematical graphs. The expectation that students of STEM should be able to encode and decode visuals that provide both quantitative and qualitative information requires a broader approach. This paper proposes a comprehensive classification of visuals that will facilitate the Wall and Benson approach to the teaching and learning of all types of visuals encountered in STEM. It permits a multidisciplinary approach to teaching visual literacy that makes explicit links between the content of the learning areas of STEM and other disciplines.

2. Classification of Visuals

The traditional approach to the teaching of visuals is to classify them by purpose or topic, with little purposeful transfer of knowledge between topics. For example, number lines, linear measuring scales (of all types), protractors, and electrical meters are taught separately in the various learning areas of STEM, implying that they differ from each other. However, it is the *characteristics* (properties) of a visual (e.g., scale, direction, shape, colour) that primarily determine how it is decoded. An approach that aims to classify and teach visuals according to their properties is more likely to assist STEM students in making meaning and in transferring knowledge between visuals with similar properties.

Mackinlay (1999), who sought to codify two dimensional quantitative graphical presentations for use in software engineering, provided a basis for such an approach. He utilised 13 perceptual elements, described by Cleveland and McGill (1984), that can be used to convey information: position; length; angle (orientation); gradient; area; volume; density; colour saturation; colour hue; texture; connection; containment; and shape. The perceptual elements were linked to particular encoding techniques to create what Mackinlay referred to as six *graphical languages*. This classification was adopted by Lowrie and Diezmann (2005; 2007) and applied to the field of education as a framework for analysing students' understanding of visuals in mathematics. These studies recommended that 1) teachers should make explicit links between graphical languages to facilitate cognitive transfer in students, 2) that broad learning opportunities should include graphical languages that are typically used outside formal mathematics contexts, and 3) that students should be given many varied opportunities to practice in different graphical languages. This paper proposes a way of implementing this advice.

As the Mackinlay (1999) classification was not developed for educational use, it has a number of shortcomings as a teaching tool. Firstly, the classification was restricted to two-dimensional static presentations of relational data. In consequence, it was not inclusive of many types of visuals commonly used in STEM classrooms, such as three dimensional representations, non-relational visuals (e.g., illustrations and diagrams) and animations. Secondly, Mackinlay's six graphical languages used overly complicated names that could lead to student confusion. Mackinlay's classification has been adapted to make it both comprehensive and relevant for educational purposes. It is summarized in Figure 1, including simple examples of each category.

2.1. One-dimensional Visuals

One-dimensional visuals rely on the perceptual elements of position and length. They encode information on a single axis, which may be oriented in any direction, but is commonly arranged horizontally or vertically. Obvious inclusions are: number lines; scales on measuring devices such as rulers, tape measures, jugs, and thermometers; time lines; and divided bar graphs. However, if the axis is curved, it also includes images of devices such as protractors, speedometers, tachometers, analogue

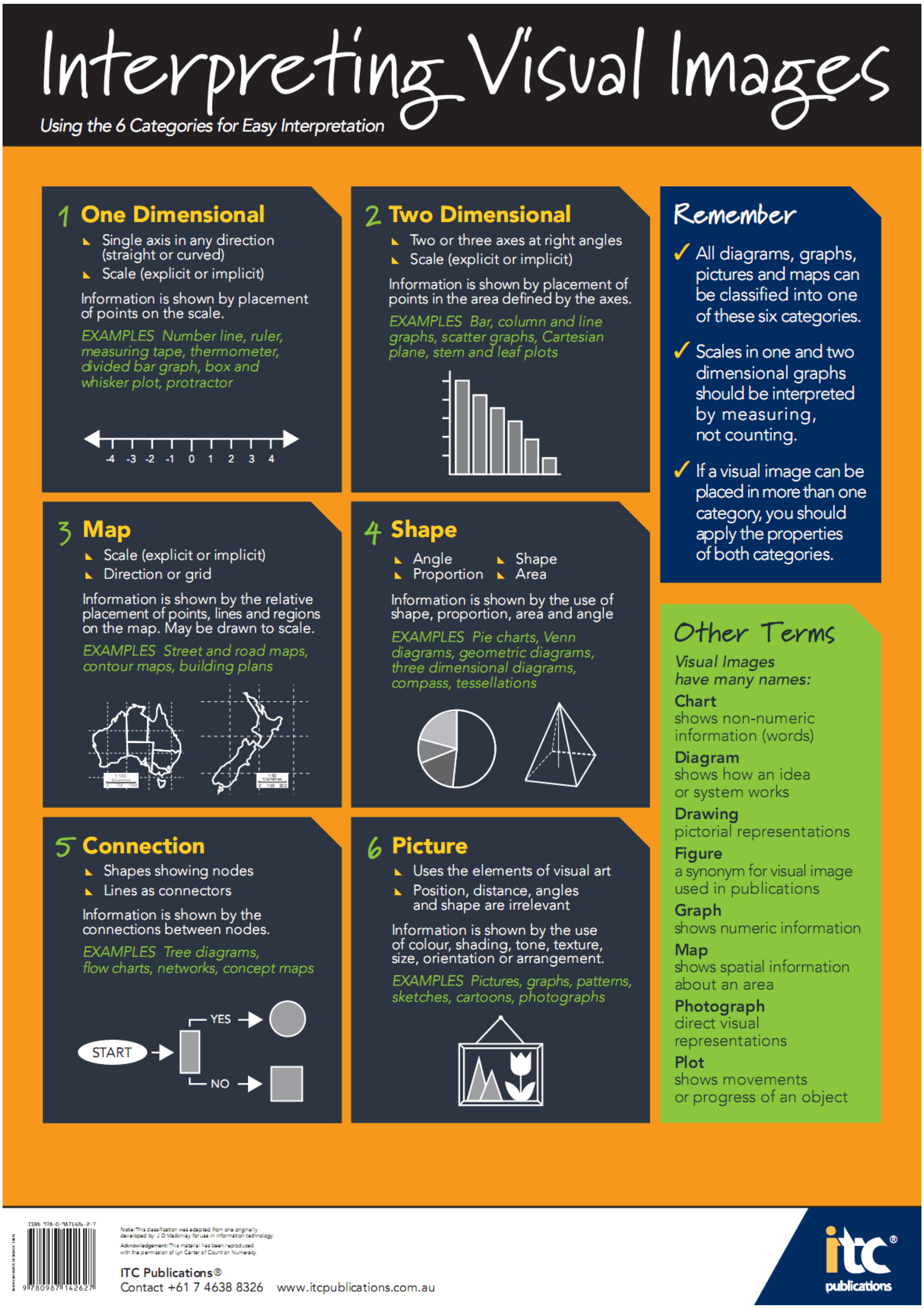

Figure 1. Classification of visuals (Carter, 2011)

(reproduced with permission of ITC Publications)

clocks, fuel gauges, and voltmeters. The common feature of all of these visuals is that they display univariate information. Values are usually marked on the single axis as points or line intervals. Distance is shown by the position of the point(s) relative to zero, or the position of two or more points relative to each other. Scale is often shown explicitly by labelled graduations on the axis. Alternatively, the labelling of key points or the relative placement of points may imply a scale.

A study of Year 5 students by Diezmann and Lowrie (2006) showed that many students were unable to identify unnumbered marks on a number line. Some interpreted the marks on the number line by counting, seeing position as the only relevant property (overlooking the importance of distance). As other visuals rely on the same concepts of position and distance, it is likely that the Diezmann and Lowrie findings could be extended beyond number lines. The possibility of extrapolating findings in this way demonstrates the power of using this method of classification of visuals.

2.2 .Two-dimensional Visuals

Images in this category encode information by use of mark(s) positioned in the region(s) defined by two or more axes. Included in this category are: line graphs; bar and column graphs; scatterplots; conversion graphs; travel graphs; Cartesian planes; and Cartesian plots of vectors and complex numbers. The common feature of all of these visuals is that they display bivariate information. *Two-dimensional visuals* can be considered to be a composition of *one-dimensional visuals*. It follows that they also rely on the perceptual elements of position and length.

The axes are generally arranged orthogonally, but it is not an essential requirement (for example, vectors can be projected onto any arrangement of axes). One of the axes may be used to represent nominal data, but at least one axis must show numerical data using an explicit or implicit scale. Students' understandings of scale developed in the one-dimensional situation can be transferred to the two-dimensional situation (and vice versa). However, the connection between the two categories of visuals must be made explicit to students. Three-dimensional Cartesian graphs and three-dimensional vectors in Cartesian form have such strong connections to the Cartesian plane and two-dimensional vectors, respectively, that they are included in the same category. In three dimensions, marks can be points, lines, planes or spaces.

2.3. Map Visuals

Map visuals encode information through the spatial location of marks. The common features of visuals in this category are scale and location, which translate to the perceptual elements of position, length, and gradient. It follows from this description that this category includes maps of all types and projections, scale drawings including plans and blueprints, photographic enlargements and reductions, polar plots of vectors, and mod-arg plots of complex numbers.

The use of scale in maps and other visuals in this category is mathematically the same as the use of scale in the *one-dimensional* and *two-dimensional* categories. However, *map* visuals usually show the scale as part of the key, rather than by use of axes. The position of a mark on a map may be described by comparison with a grid overlay (using latitude and longitude, grid reference or map coordinates) or relative to another mark using distance and gradient (also called direction or bearing). Grid references in maps have similarities to coordinates in some graphs in the *two-dimensional* category. The similarities between visuals in the *map* and other categories, especially the treatment of scale, may not be obvious to students. Teachers must ensure that students are able to connect these ideas.

2.4 .Shape Visuals

Shape visuals share the perceptual elements of shape, gradient, and containment (enclosure of space). Examples in this category include: plane shapes, geometric solids, geometric diagrams (using lines, angles, and plane shapes), pie charts, Venn diagrams, transformations and tessellations. Position, length (scale) and gradient are not explicitly shown in *shape* visuals, although the visual may be drawn with precision (for example, in pie charts or plane shapes). If information about position, length or gradient is needed to decode the visual, it is marked using labels or annotations.

2.5 .Connection Visuals

Connection visuals encode information by connecting two or more nodes. Visuals in this category can be subdivided into two groups (Novick, Hurley, & Francis, 1999). Firstly, there are path-like representations, including networks, flow charts, concept (mind) maps, electrical diagrams, and critical path diagrams. The second group is hierarchical, including tree diagrams, evolutionary charts, cause and effect diagrams, and taxonomies. Visuals in both groups rely on the perceptual element of connection.

Connection visuals usually consist of nodes, representing the key concepts, and interlinking lines showing the connections between the nodes. In most *connection* visuals, gradient and distance are irrelevant, with the relative placement of nodes determined for reasons of clarity. Nodes are most commonly connected using lines, which may indicate directionality. The magnitude of connections, if relevant, may be indicated by the use of labels, but not scale. Some visuals may to indicate the nature of connections by the use of size and relative position instead of lines, for example, when a triangle or pyramid is subdivided using horizontal lines to indicate a hierarchy, as occurs in illustrations of a food group pyramid.

2.6 .Picture Visual.

The six retinal properties of colour hue, colour saturation, shape, size, texture, and angle (orientation) are relevant to *picture* visuals. Unlike the other categories, they often provide qualitative information. STEM examples include: illustrations, sketches, photographs, picture graphs, diagrams, and icons. The category also includes artworks that enhance the quality of our lives. The six perceptual elements may also apply to visuals in other categories, for example, maps make use of some retinal properties to convey information. However, the difference in the *picture* category is that the retinal properties are the most important aspect of the visual. The measureable elements of position, length, and gradient are either less important or irrelevant. Magnitude cannot be conveyed visually, but can be indicated using labels or annotations.

It is tempting to conclude that visuals in the *picture* category are less relevant to the STEM learning areas. However, a perusal of the NAPLAN numeracy tests (ACARA, 2010, 2011, 2012; MCEECDYA, 2009; MCEETYA, 2008), indicates that about 40% of the visuals used in the tests fell into this category.

2.7. Combinations

As with any classification, some visuals have features that belong to more than one category. For example:

representations of organic molecules (in the *shape* category) also include important information about the *connections* between the various atoms;

geometric constructions (in the *shape* category), if drawn to scale, share some characteristics with visuals in the *map* category; and

one dimensional visuals such as analogue clocks could also be defined in terms of the angle subtended at the centre of the circle and thus be classified in the *shape* category.

Where this occurs, learners can draw on the properties of visuals in both categories.

2.8. Moving Images

The discussion so far has considered only static visuals. However, software now enables students to use and create moving images such as video clips, animations, or dynamic graphs. The classification caters for moving images by placing them in the same category as the sequence of underlying static visuals that form the moving image.

3. Teaching Strategies

This paper proposes a different pedagogy for learning about visuals. It encourages learners to consider a visual image in the context of all other visuals (that is, the “big-picture”). It suggests that a pedagogy that focuses on feature-similar visuals, by explicit use of the classification proposed above, may assist students in transferring their knowledge and understanding from a familiar to an unfamiliar context, both within and between categories. It is not proposed that teachers change the existing topic-based approach to teaching students about visuals in STEM. However, making links to similar visuals by reference to the classification and encouraging the transfer of knowledge from the familiar to the unfamiliar, can be incorporated into existing approaches. If it is adopted across learning areas and year levels, using a common metalanguage, students will come to see the connections between the visuals used in STEM, encouraging the cross-curricular transfer of knowledge and skills.

The pedagogy in each classroom can be similar. If, when first encountering an unfamiliar visual image, students are encouraged to consider the placement of the image within the classification, they can draw on the skills that they would use to interpret other, more familiar visuals in the same category. To achieve this, teachers must show students how to deconstruct a visual using questions such as *Is this graph (diagram, chart, ...) similar to anything we have seen before? What information does it show? How many variables are there? Is it drawn to scale? Does direction matter? What is important? What is not important? How does it help us? Why is it used in this situation?*

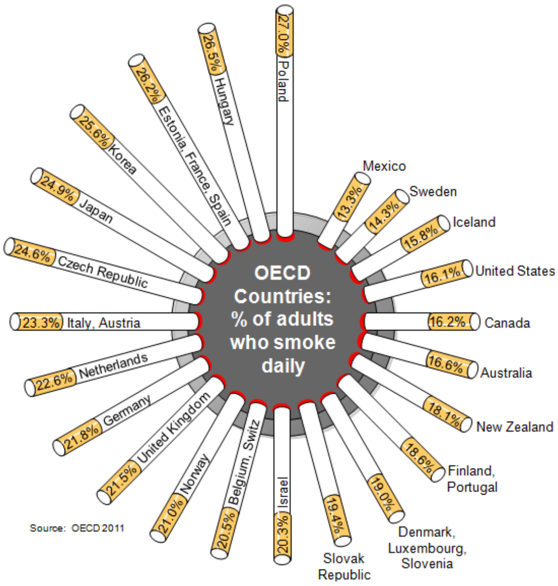

Figure 2. Two-dimensional visual image

(adapted from an image found at http://www.time.com/time/interactive/0,31813,1911060,00.html)

To illustrate this approach, it is unlikely that most school students would have previously encountered the visual in Figure 2. However, by following the prompts, students may observe some similarities to a column graph, albeit with differences in the axes. The axis that is usually horizontal in a column graph is circular in this case. The axis that is usually vertical in a column graph, showing scale, is omitted in this case, but there is a scale implied by the labels on or near each of the 'cigarettes'. They can determine (by prompting, if necessary) that these differences in the axes do not affect the overall interpretation of the graph. They might also note that the use of colour in each of the 'cigarettes' is unimportant. This should eventually lead to the conclusion that this visual belongs to the *two-dimensional* category. Students are now able to apply the skills that they have previously used to interpret other, more familiar *two-dimensional* visuals. In this way, the learning experiences focus on the transfer of skills from the familiar to the unfamiliar. A deeper analysis of the visual could lead to consideration of why the author/artist chose not to represent this information using the standard column graph format, providing students with insights that they can apply when creating their own visual images.

A similar approach can be taken in the case of Figure 3. It reveals that the visual shows information horizontally, using an implicit scale. The vertical placement of information is irrelevant – whilst radio waves may have long wavelength and low frequency, they have nothing to do with red light. This places the visual in the *one-dimensional* category. In fact, it a combination of three related *one-dimensional* visuals, showing the wavelength and frequency of the electro-magnetic radiation, the names used to describe the full spectrum of the electro-magnetic radiation, and an exploded view of the colours of the visible light spectrum. Once students have identified the one-dimensional nature of this visual, its interpretation is simplified. The skills used to interpret number lines can be applied to each of the three sections individually. Students are then required to use their skills of comparison to connect the three sections.

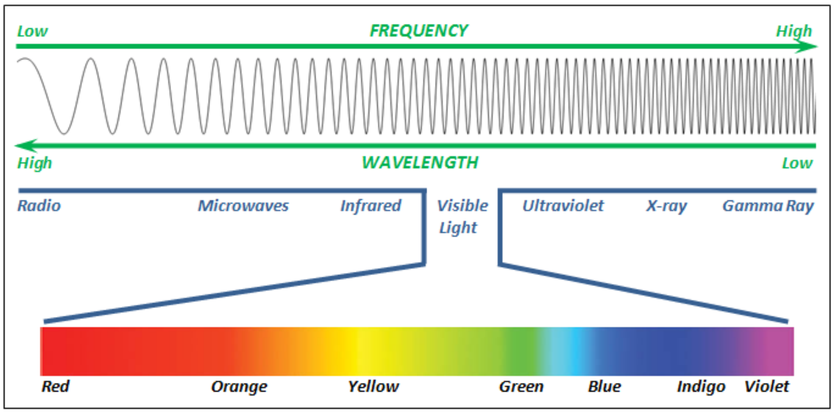

Figure 3. One-dimensional visual image

(adapted from on an image found at http://bmsscience8209.edublogs.org/files/2011/03/spectrum-2g5oqdz.gif)

4. Conclusion

Development of the skills of visual literacy (the decoding and encoding of visual information and thinking visually) is relevant to all areas of STEM. The skills must be learned, drawing on prior experience and context. Not only should students of STEM be able to work in familiar contexts, they must also be able to decode visuals that are unfamiliar. This paper has proposed a classification of visuals in six parts: *one-dimensional*; *two-dimensional*; *map*; *shape*; *connection*; and *picture*, summarised in Figure 1. If visual literacy is developed using this classification, then students will learn to cope with visuals that they have never seen before.

The paper has proposed an enhancement of traditional teaching methods to assist students in developing visual literacy. It is important that students also consider the different categories of visual so that they can see how the visual being studied fits into the ‘big picture’ and transfer the skills learned in familiar situations to those that are unfamiliar. This will allow them to acquire the analytic tools to cope with the very wide variety of visuals encountered in STEM.

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