Learning with Visual Representations through Cognitive Load Theory

Bogumila Jankowska Gierus

Educational Psychology - Learning Sciences Stream

McGill University, Montreal

July, 2011

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Masters of Arts.

TABLE OF CONTENTS

Abstract

This study examined two different strategies of learning with diagrams: drawing diagrams while learning or learning from pre-constructed diagrams. One hundred ninety six junior high school students were randomly placed in a condition either to draw while learning about how airplanes fly or to study from pre-constructed diagrams. Before the learning, students' prior knowledge and elaboration strategies were measured. During learning in either condition, students reported their mental effort. Afterwards, students' learning was tested on both a similar task and transfer task. Cook's (2006) theoretical framework, which combines prior knowledge and cognitive load theory on visual representations in science education, was used to analyze the results. Results showed that students' mental effort significantly increased in the drawing condition, yet results on the posttest were mixed. Students did not do better, and sometimes did worse, on the posttest measures when they learned by drawing diagrams versus using pre-constructed diagrams to learn. The exception was that students with low initial prior knowledge did do better. Elaborations strategies did not have an effect on students' achievement or mental effort in either condition.

Cette étude a examiné deux stratégies différentes d'apprendre à l'aide des diagrammes: le dessin de diagrammes tout en apprenant ou en apprenant sur la base des diagrammes préconstruits. Cent quatre-vingt-seize étudiants de lycée ont été aléatoirement placés dans une condition où soit ils dessinaient tout en se renseignant sur la façon dont les avions volent ou étudiaient à partir des

diagrammes préconstruits. Avant l'étude, les stratégies de connaissance et d'élaboration des étudiants ont été vérifiées. Pendant l'étude sous l'une ou l'autre des conditions, les étudiants signalaient leur effort mental. Suite à cela, l'étude des étudiants est examinée sur une tâche semblable et une tâche de transfert. Cadre théorique de Cook (2006), qui combine la théorie de la connaissance antérieure et de charge cognitive sur les représentations visuelles dans l'éducation de la science, ont été employés pour analyser les résultats. Les résultats ont prouvé que l'effort mental des étudiants a augmenté sensiblement sous condition de dessin, pourtant les résultats sur le post-test étaient mitigés. En règle générale, les étudiants ont fait plus ou moins mauvais sur les mesures de post-test quand ils ont appris en traçant des diagrammes au contraire de l'utilisation des diagrammes préconstruits pour apprendre. Cependant, les étudiants ayant une faible connaissance de base ont mieux exécuté le post-test en traçant leurs propres diagrammes. Les stratégies d'élaborations n'ont pas exercé d' effet sur l'accomplissement ou l'effort mental des étudiants pour chacune des conditions.

Introduction

"A picture is worth a thousand words" refers to the notion that a complex idea can be conveyed with just a single still image. In science, complex ideas are commonplace and diagrams, images, and models are used in everyday work (Kozma, Chin, Russell, & Marx, 2000). How is this powerful tool of imagery used in science education? How do people use visual representations in their learning (Cox, 1999; DiSessa, 2004; Zhang, 1997)? These are some of the broader ideas I explored for my Masters thesis. In particular, I compared learning from a pre-constructed visual representation to learning by self-constructing visual representations. My specific research question is: Given students' prior knowledge and use of elaboration strategies, which method of learning results in better learning outcomes (i.e., higher performance on similar task and higher transfer performance) – translation of a text into a visual representation or internalization of pre-constructed diagrams?

Using Sweller's cognitive load theory (Sweller, 1988; Sweller, 1994; Sweller, van Merrienboer, & Paas, 1998; van Merrienboer & Sweller, 2005) as the theoretical foundation, I examined how visual representations are used as learning methods in the scientific domain. In particular, the theoretical framework for this study is based on Cook's (2006) extended version of cognitive load theory, which integrates individual differences, such as prior knowledge, and visual representations into science learning and instruction. First, I will define visual representations. In the next section I will discuss cognitive load theory, its premise and implications for instructional design. Third, I will distinguish between the two ways of learning with visual representations, namely analyzing them or constructing them. I compare these two modes of visualization (Stylianou, 2002) based on a literature review of visual representations, followed by a re-examination of the differences between the two modes through cognitive load theory. I then describe the purpose, research question, and hypotheses, delineate the methodology and present the results. The thesis ends with a discussion of the findings, future directions, and limitations to the study.

Definition of Visual Representations

In his ground breaking work on external representations and problem solving, Zhang (1997) defines external representations of the knowledge and structure in the environment as physical symbols, objects, or dimensions (e.g., written symbols, beads of abacuses, dimensions of a graph, etcetera), and of external rules, as constraints or relations embedded in physical configurations (e.g., spatial relations of written digits, visual and spatial layouts of diagrams, physical constraints in abacuses, etcetera). The information in external representations can be perceived, analyzed, and processed by perceptual systems alone, although the conceptual knowledge from internal representations can sometimes facilitate or inhibit the perceptual processes (Zhang, 1997). There are several types of external representations, two of which include verbal representations and visual representations. The key difference between verbal and visual representation is that imagery is regarded primarily as a parallel processing system where images present themselves simultaneously and are characterized by their spatial arrangement (Selfe, 1985), whereas verbal representations are usually presented and decoded linearly.

In the present study, not all external representations are considered. Rather, the focus in this study is on visual representations. More specifically, I will look at learning from diagrams and pictures. This type of visual representation can be used by a teacher, included in a textbook or learning software, or drawn by a student while learning. As a basis for the analysis of visual representations and how they are processed by learners, I used cognitive load theory. In the next section, cognitive load theory is explained as it relates to visual representations and to the present study.

Cognitive Load Theory

Cognitive load theory describes the way that humans process information and learn. According to Sweller (Sweller et al., 1998), it was developed largely to provide guidelines to assist in the presentation of information in a manner that encourages learner activities that optimize intellectual performance. Therefore, it provides both a model of human cognitive processing coupled with instructional recommendations.

Human cognitive architecture. Sweller (1988) describes human cognitive architecture as follows: We have a limited working memory that deals with all conscious activities and an effectively unlimited long-term memory that can be used to store schemas of varying degrees of automaticity. Any cerebral activity involves putting a cognitive load on this limited working memory. Intellectual skill comes from the construction of large numbers of increasingly sophisticated schemas with high degrees of automaticity. Schemas bring together multiple elements that can be treated as a single element and allow us to ignore myriads of irrelevant elements. When this happens, working memory is freed, allowing processes to occur that otherwise would overburden working memory. Automated schemas allow fluid performance on familiar aspects of tasks and – by freeing working memory capacity – permit levels of performance on unfamiliar aspects that otherwise might be quite impossible (Cook, 2006; Sweller, 1988; Sweller, 1994; Sweller et al. 1998; van Merrienboer & Sweller 2005). However, the key consideration in this theory is the limited working memory and cognitive load that is placed on this working memory.

Types of Cognitive Load

According to Sweller (Sweller et al. 1998; van Merrienboer & Sweller, 2005) and Mayer (DeLeeuw & Mayer, 2008), there are three types of cognitive load: intrinsic, extraneous, and germane. Intrinsic cognitive load is the essential load for comprehending the material, and depends on the complexity of material; namely, the number of interacting elements that must be kept in mind at any one time (Sweller et al., 1998; DeLeeuw & Mayer, 2008). All instruction has an inherent difficulty associated with it, referred to as intrinsic cognitive load. This inherent difficulty may not be altered by an instructor. However, many schemas may be broken into individual sub-schemas and taught in isolation, to be later brought back together and described as a combined whole (Chandler & Sweller, 1992). The working memory load imposed depends on the number of elements that must be processed simultaneously in working memory (Sweller, 1994). For example, a student reads the following sentence: "The force created by lift needs to be greater than the weight of the plane in order for the airplane to take off." In this sentence, the student needs to understand the meaning of lift, weight, the interaction between them (that lift is greater than weight) and the result that comes about due to this interaction (airplane takes off). There are four elements here that must be considered simultaneously for the sentence to make sense. These four elements comprise the intrinsic cognitive load.

In contrast, extraneous cognitive load is generated by the manner in which information is presented to learners and is under the control of instructional designers (Chandler & Sweller, 1992). This load can be attributed to the design of instructional materials. Because there is a single, limited cognitive resource, i.e. working memory, using resources to process extraneous load reduces the amount of resources available to process intrinsic load and germane load (i.e., learning). Thus, especially when intrinsic and/or germane load is high (i.e., when a problem is highly complex), materials should be designed so as to reduce extraneous load (van Merrienboer & Sweller, 2005). Following the example from above on lift and weight, if a student is trying to understand the sentence, extraneous cognitive load might increase if the sentence is written in a foreign language. In this case, the student not only needs to understand those four interacting elements listed above, but will also have to translate the words and understand the interactivity of those words. On the other hand, extraneous load could be reduced for this sentence by using a diagram to demonstrate the relationship among lift, weight, and outcome.

Finally, germane load is the load devoted to the processing, construction and automation of schemas (Sweller et al., 1998). Germane load is activated when the learner engages in deep cognitive processing such as mentally organizing material and relating it to prior knowledge (DeLeeuw & Mayer, 2008). For our example, if a student uses his or her prior knowledge of weight and lift, he or she might incorporate the interaction (lift greater than weight) – outcome (plane takes off) relationship into his/her schema of why planes take off. This thought, however, takes up working memory and therefore would increase the student's cognitive load. But since it is used for schema construction or organization, this is considered germane cognitive load.

Whereas intrinsic load is generally thought to be unalterable, instructional designers can manipulate extraneous and germane load (van Merrienboer & Sweller, 2005). Sweller (1994), among others, (Cook, 2006; DeLeeuw & Mayer, 2008; Sweller et. al. 1998) suggests that instructional designers should limit extraneous load and promote germane load. For example, Cook (2006) explains how using diagrams in science instruction may decrease extraneous cognitive load and at the same time increase germane cognitive load. In short, germane cognitive load is when learning takes place. The burden placed on working memory can be reduced by increasing the capacity or reducing cognitive load (Cook, 2006).

Reducing Cognitive Load or Increasing Working Memory Capacity

One possible way to reduce cognitive load is by constructing schemas and automation (Sweller et al., 1998). According to Sweller (1994), knowledge is stored in long term memory in schemas, which help organize and link relevant information together. Although schemas can hold a large amount of information, they are processed as a single unit in working memory. As a result, cognitive schemas reduce the burden on working memory to only a few elements of information at one time (Sweller, 1994). High levels of prior knowledge imply that schemas have previously been constructed and can be retrieved easily (Cook, 2006). Working memory is more likely to be overloaded when it has fewer and/or simpler schemas to draw from, which is common for individuals with low prior knowledge (Cook, 2006).

When the material imposes a low-intrinsic load due to the expertise of the learner or the low complexity level of the material, the quality of instructional design is less likely to have an impact because there is enough memory space remaining to compensate for poor design (Sweller 1988, Sweller et al., 1998). When this occurs, the appropriate goal would be to encourage germane cognitive load, and the creation of schemas or automation (Cook, 2006; van Merrienboer & Sweller, 2005).

In contrast, when intrinsic load is high, schema formation will require more effort, and thus it is essential to minimize extraneous cognitive load (Sweller, 1988; Sweller, 1994; Sweller et al. 1998). External representations, like diagrams, can be used as a form of cognitive offloading, especially when intrinsic load is high (Scaife & Rogers, 1996). When extraneous load is reduced, more resources are free for intrinsic cognitive load (for processing the information) or germane load (for learning the concepts). With this automation and schema production, intrinsic load is reduced even more (Cook, 2006), allowing for more processing and learning to occur. From this logic, it is apparent that prior knowledge has a significant influence on cognitive load.

Prior knowledge affects cognitive load. From the numerous studies on visual representations in science education, there is considerable evidence that prior knowledge influences perception and attention: Learners use prior knowledge to select relevant information from graphics, add information from their prior knowledge, and develop a mental model (Kozma & Russell, 1997; Stylianou & Silver, 2004; Kohl & Finkelstein, 2008). From a cognitive load perspective (Sweller, 1994), prior knowledge determines which schemas or units of input will be copied into working memory. If the schemas are sophisticated and automated, working memory is not overburdened and therefore learning may take place. However, if the learner is a novice, possessing non-automated or simpler schemas, working memory might become overloaded with the simplest activities (Sweller, 1994). Therefore, knowing or at least estimating learners' prior knowledge is a key component to choosing the types of instructional activities that will be effective.

To summarize, each instructional activity has an intrinsic unalterable cognitive load, which depends on the number of interconnected elements that need to be used simultaneously, an extraneous cognitive load, which should be minimized by the instructor, and a germane cognitive load, which should be increased whenever possible, as this is when learning, i.e. construction and automation of schemas, takes place. Moreover, there is a low-level perceptual stream of information constantly entering sensory buffers in the perceptual systems of the brain. However, there is a limited capacity for further processing of this information and linking it to prior knowledge (Cook, 2006). All of the cognitive loads add up (Sweller, 1994) and if the limited working memory is overloaded then no learning or understanding will take place.

In this regard, the instructor must ensure that learners are not overburdened (Sweller, 1994, Sweller et al., 1998). For instance, an instructor might want to: increase working memory by using both audio and visual information, adjust extraneous cognitive load, divide the instruction into lower level chunks, or even forego germane knowledge construction for the primary purpose of understanding (van Merrienboer & Sweller, 2005). Thus, instructional methods can draw from cognitive load theory to benefit the learner. In the following section, the relevant instructional methods to this study will be discussed.

Instructional Methods Derived from Cognitive Load Theory

Over the last two decades, many instructional methods have been developed and empirically tested based on cognitive load theory (van Merrienboer & Sweller, 2005). These instructional methods have been designed to decrease extraneous load, increase germane load, reduce intrinsic load, or increase working memory.

Decreasing extraneous cognitive load. One popular method that has been used to decrease extraneous cognitive load is the use of goal-free problems as opposed to traditional problems (Sweller, 1998). Goal-free problem solving is a strategy that decreases extraneous cognitive load (Sweller, 1998). When solving traditional problems, students must keep the goal of the problem in their working memory. This reduces space in working memory for intrinsic and germane cognitive load. In contrast, a problem without a specific goal reduces this extraneous cognitive goal because the goal is no longer taking up working memory space. If the intention of the problem solving activity is to have students construct schemas, then finding the solution to one specific question is not necessary (Sweller, 1988). An example of a goal-free problem is obvious in trigonometry: A teacher could ask a student to “solve the triangle” (i.e. to find all the angles and sides) instead of “find the length of this particular side.” Without specifying a particular side, the student does not need to remember this information, which frees up cognitive resources.

Van Merrienboer and Sweller (2005) list other instructional methods that reduce extraneous cognitive load: worked examples, completion problems, and problem solving support. Worked examples focus attention on solution steps, enabling learners to induce generalized solutions or schemas. According to a review by Sweller and colleagues (1998), many studies have demonstrated that studying worked examples lead to schema construction more than actually solving equivalent problems. Completion problems are similar to worked examples, but with key sections of the solution steps missing. Whereas worked examples do not compel learners to carefully study them, completion problems require the learner to examine the worked example and fill in the missing steps (Sweller et al., 1998).

Problems solving support is yet another way to reduce extraneous cognitive load when problem solving. For example, a student might use some kind of process worksheet that provides a description of the phases one should go though when solving a problem and that provides hints or rules-of-thumb that help the student successfully complete each phase of the problem solving process. However, results from studies are mixed as to the benefits of this instructional strategy: it is possible that the process worksheet, instead of decreasing extraneous cognitive load, might actually increase it as more elements need to be processed simultaneously, thereby overloading working memory (review by van Merrienboer & Sweller, 2005).

Increasing germane cognitive load. Once extraneous cognitive load is decreased, there is more room in working memory for construction and automation of schemas. This process of learning is germane cognitive load. According to Sweller (1994; Sweller et al., 1998), worked examples and completion problems decrease extraneous cognitive load, but also help with the construction of schemas thereby increasing germane cognitive load. For example, when a student analyzes a worked example, he/she sees how the problem can be solved which aids in the development of his/her schema for how this particular problem may be solved (Sweller, 1994). However, to achieve transfer of that schema to another problem or another context, other instructional methods have been observed to be beneficial, such as the variability effect and the self-explanation effect (van Merrienboer & Sweller, 2005).

Transfer and the self-explanation effect. In recent years, as pointed out by van Merrienboer, Kester and Paas (2006), more cognitive load research has focussed on methods for increasing germane load, such that problem solving and transfer of learning can occur. Transfer refers to the process and the extent to which past experiences and prior knowledge affect learning and performance in a current novel situation (Ellis, 1965). Importantly, transfer is central to designing and developing effective instruction. Bruer (1994) emphasizes that

> "Problems of transfer pervade schooling. Teachers want to teach lessons so that students can transfer what they have learned during class instruction to solve new problems at the end of a chapter. We want that learning to transfer to the unit, semester, or standardized test. Most important, we want school learning to transfer to real world problem

> solving at home and on the job. If this is our goal, what and how should we teach?” (p. 53)

In this regard, instructional methods that induce germane load, which in turn induce transfer, are essential to the learning process.

According to Ainsworth and Loizou (2003), the self-explanation effect is one way of inducing germane cognitive load. The self-explanation effect occurs when a student explains to him/herself the meaning of a certain sentence, diagram, or concept (Ainsworth & Loizou, 2003; van Merrienboer & Sweller, 2005). Some students do this spontaneously, whereas others are more reluctant to elaborate on the concepts that they learn (Pintrich, Smith, Garcia & McKeachie, 1993; Weinstein and Palmer, 1990). These students, called low-elaborators, do not connect one schema to another as easily and need prompting to self-explain and see the connections. Importantly, the self-explanation effect has been documented to increase schema construction (conceptual learning) with the use of visual representations (Ainsworth & Loizou, 2003). The way visual representations can increase working memory is a key consideration of this study. Therefore, this modality effect will be described next.

Increasing working memory capacity and the modality effect. To increase working memory capacity seems counter to the cognitive load theory model of human cognition. After all, cognitive load theory is based on the fact that working memory is limited. So how is it possible to increase this limited working memory? Sweller (1998) explains that working memory has partially independent processors that are associated with individual sensory modes. For instance, Baddeley (1992) divides working memory into a “visual-spatial scratch pad" for dealing with visually based information and a "phonological loop" to deal with auditory, primarily speech-based, information. These two systems are governed by working memory. In this way, working memory capacity may be increased by using multiple processors, rather than by a single processor (Sweller et al., 1998).

The instructional effect that directly follows from this theory is the modality effect. The modality effect takes advantage of both visual inputs and auditory inputs occurring simultaneously (Cook, 2006; Sweller et al., 1998). When both the visual and the auditory inputs are used together, working memory capacity is increased allowing for more complex learning, higher intrinsic cognitive load, and higher germane cognitive load. So how is cognitive load measured? This is described next.

Measuring Cognitive Load

Three major categories of mental-effort measurement techniques can be classified (DeLeeuw & Mayer, 2008; Wierwille and Eggemeier, 1993). These include subjective, physiological, and task- and performance-based indices. Subjective techniques are based on the assumption that people are able to introspect on their cognitive processes and to report the amount of mental effort expended (Ayers, 2006; DeLeeuw & Mayer, 2008; Paas & van Merrienboer, 1994). Physiological techniques are based on the assumption that changes in cognitive functioning are reflected in physiological measures, such as heart rate variability, brain activity, and eye activity (Paas & van Merrienboer, 1994). Task- and performance- based techniques include two subclasses of techniques: primary task measurement, which is based on learner performance of the task of interest, and secondary task methodology, which is based on performance when a second task is performed concurrently with the primary task (Paas & van Merrienboer, 1994).

Typically, working memory has been measured with task- or performance-based techniques. For example, using computational models and secondary tasks, Sweller (1988) provided evidence of a substantial reduction in cognitive load when using goal-free as opposed to a conventional problem solving strategy. Similarly, Hoffman and Schraw (2009) used a letter recoding task to measure students' working memory capacity to see how working memory influences problem-solving efficiency. However, the least intrusive way of measuring mental effort without interfering with the instructional methodology is the subjective measure (Paas & van Merrienboer, 1994).

A comparison between subjective and physiological measurement techniques (DeLeeuw & Mayer, 2008; Paas, 1992; Paas & van Merrienboer, 1994; Wierwille and Eggemeier, 1993) shows that the subjective rating scale is sensitive to relatively small differences in cognitive load, and that it is valid, reliable and nonintrusive. The physiological measurement technique is also non-intrusive, but largely invalid, and only sensitive to relatively large differences in cognitive load (Paas & van Merrienboer, 1994). Therefore, Sweller and colleagues (1998) concluded that the subjective rating is a promising technique to measure mental effort. More recently, Ayres (2006) used a subjective measure to detect intrinsic cognitive load, whereas DeLeeuw and Mayer (2008) showed that the subjective measure is the best one out of the three to measure germane cognitive load. Therefore, in this study, to measure cognitive load while learning by studying diagrams or by drawing diagrams, the subjective rating method was employed. In the following section, these two methods of learning with visual representations are discussed.

Comparing the Two Ways of Learning with Visual Representations

Stylianou (2002) proposes that there are two modes of using visual representations. Each visualization is a translation, either from external to internal models (e.g. imaging in the mind), or internal to external representations (e.g. drawing) (Stylianou, 2002). Therefore, a student can either observe a diagram then translate it into his/her own internal representation, much like "reading" the diagram; or a student can try to externalize his/her internal representation into a diagram, similar to "writing" of a diagram. This study is primarily concerned with the comparison of these two translations.

Understanding and Learning from Visual Representations. To understand how students learn from standard textbook visual representations, it is necessary to do a novice-expert comparison and thus determine what is important in the "reading" of diagrams. For example, Kozma and Russell (1997) examined differences between experts and novices on sorting of different chemical phenomena presented in multiple types of representations (diagrams, balanced equations, structural models, videos of an actual chemical reaction, animation of a chemical reaction on the molecular level, etcetera). In their second experiment, the researchers had the experts and novices transform one type of representation into another. The results showed that experts used multimedia (many different kinds of media) more than novices; experts easily transformed one representation to another, whereas novices had a hard time with the transformations.

Specifically, when sorting, experts grouped the different representations into bigger chunks and used more types of representations compared to novices (Kozma & Russel, 1997).

In another study observing chemistry experts, Kozma and colleagues (2000) analyzed the chemists' use of representations. Going into their laboratories, meetings and places of work, the authors had the opportunity to see how chemists use visual representations in their natural habitat. They found that chemists change from one representation to another with great fluency. In fact, one of the hallmarks of being a chemist is to read and understand the different representations created by the chemists themselves or from readouts from different instruments (Kozma et al., 2000). In addition, Kozma argues that chemists use chemical structural formulas as a means of communication. Using multiple representations for chemists is part of their community of practice.

In the medical field, radiologists are often referred to as visual experts in the medical community (Wood, 1999). Wood (1999) compared the ways that expert and novice radiologists used their visual expertise. Experts initially quickly scan the x-ray and identify the abnormality. They then scan the remainder of radiograph, but return to the abnormality. While scanning, the radiologist focuses on areas that also may show a related abnormality. Novices, on the other hand, look systematically at all parts of the x-ray, starting from the peripheral of the image to the centre, and then back to the peripheral. They do not use the scanning technique, nor do they return to any parts of the visual representation after going over it once. They also do not recognize what is relevant and irrelevant. To this end, Wood states that to become a visual expert one must first learn the knowledge, and then develop a memory representation of images and patterns along with the meaning of each of these patterns.

Wood (1999) also observed that experts spent more time in the initial mental model creation and were more able to align their own schema to the specific elements and novel aspects of the case compared to novices. Novices, on the other hand, were less able to modify their schema in response to added or conflicting data. In addition, differences between experts and novices in decision making errors were related to the inability or inaccuracy of the novice representing a problem in a mental information bank. Finally, Wood suggests that speed and confidence in the early diagnostic steps allowed the expert greater time for reflection and innovation in problem solving.

In another study of the interpretation of visual representations by experts, Jucks, Bromme, and Runde (2007) examined the influence of using an external representation on experts' ability to explain a pharmaceutical concept to a layperson. Working with the illustration encouraged experts to become immersed in their own knowledge; the answers supplied to the patients were more in expert jargon. The external diagram gave experts "representational guidance." This, in turn, made the task seem easier than it was, and prevented them from explaining it properly to the lay-person (Jucks et al., 2007). In this respect, it appears that the diagram was used for cognitive offloading and, as such, experts did not correctly perceive the difficulty of the task.

Finally, in an instructional environment, Ainsworth and Loizou (2003) explored teaching aspects of the circulatory system to non-science majors using a text or a diagram. Students were presented with textual or diagramic explanations and were asked to self-explain, after which they were tested on conceptual knowledge. The results were overwhelmingly in favour of the diagrams. Not only was the amount of self-explanation greater when students learned with diagrams, those students also had a much higher score on the conceptual posttest.

From the studies above it is apparent that diagrams can be very useful in a wide variety of disciplines, such as medicine, chemistry, pharmacology, and education. They can be used for cognitive offloading (Jucks et al., 2007), communication (Kozma et al., 2000), and for conceptual learning and self-explaining (Ainsowrth and Loizou, 2003). In addition, visual representations are used more productively by experts as compared to novices (Kozma & Russel, 1997; Wood, 1999). Are the same patterns found for learning by drawing diagrams? This is discussed next.

Constructing and using self-generated visual representations. When constructing diagrams, it is presumed that experts and novices have different ways of interpreting them (Stylianou, 2002; Stylianou & Silver, 2004; Kohl & Finkelstein, 2008). In one study, Stylianou (2002) had expert mathematicians solve novel mathematics problems. Using think aloud protocols and observing their diagram construction, she was able to observe and classify experts' problem solving analysis and treatment of visual representations during the problem solving process.

Stylianou (2002) argued that diagrams provided experts with "new" information. Mathematicians did not accidentally see the additional information, but they searched for it purposefully after each drawing they constructed. Experts' prior knowledge appeared to be essential – expert mathematicians had the ability to mathematically exploit new observations given by diagrams and proceeded further, either by constructing new diagrams or arriving at a solution. Diagrams were not a goal in themselves but a means to aid mathematicians in gaining more information for the problem situation (Stylianou, 2002).

In a subsequent study, Stylianou and Silver (2004) compared experts' and novices' use of visual representations in mathematics problem solving situations. Stylianou and Silver interviewed undergraduate students (novices) and mathematics professors (experts) and had them do a sorting task of mathematics problems. The qualitative results revealed that novices see visual representations useful only in the context for which they were taught to use them (e.g. geometry). Experts, on the other hand, indicated potential use of visual representations across a wider range of problems. Counter to previous research, however, both experts and novices saw the use of visual representations as a viable strategy in advanced mathematical problem solving. While problem solving, experts constructed visual representations more frequently than novices, and used them as dynamic objects to explore the problem space qualitatively, to develop a better understanding of the problem situation, and to guide their solution planning and enactments of problem solving. Novices also frequently used diagrams in problem solving, however, they made little use of their representations. The experts recognized meaningful patterns in the diagrams they constructed. They seemed to have a rich schematic structure associated with the possible operations they could employ on visual representations, which allowed them to use the diagrams they constructed. Novices, on the other hand, knew little about how to make diagrams a helpful tool due to their lack of prior knowledge (Stylianou & Silver, 2004).

In another novice-expert study on diagram construction utility, Kohl and Finkelstein (2008) examined differences between first year undergraduate students (novices) and first year physics graduate students (experts) as they solved atypical physics problems. Their findings point to some clear differences: experts solved problems more quickly; exhibited more careful analysis, planning, and self checking; had a more flexible starting point; were able to flow from one representation to another more smoothly and rapidly; and, were more flexible with their internal schema, compared to novices, who had more rigid internal models.

Kohl and Finkelstein (2008) found, however, that experts and novices used the same amount of representations in their problem solving. In contrast, similar to Stylinaou's and Silver's (2004) study, Kohl and Finkelstein showed that novices used these multiple representations without really understanding how they helped in the problem solving process, or how to use them. Experts used pictures to make sense of the problem, whereas novices did not quite know how to use the picture they constructed (Kohl & Finkelstein, 2008).

Several other studies have also demonstrated the usefulness of diagram construction (Edens & Potter, 2001; Gobert & Clement, 1998; Hsieh & Cifuentes, 2003; Parnafes, 2009). For example, Gobert and Clement (1998) found that constructing diagrams, compared to writing summaries while learning a complex scientific phenomenon, is extremely advantageous in terms of conceptual understanding. In addition, Edens and Potter (2001) also investigated the effects of student-generated visualization on conceptual learning. They had students draw, recopy a diagram, or write summaries of what they learned that day in science class. Edens and Potter found that students who drew (both their own representations and the ones that recopied a diagram from a textbook) performed significantly better on the conceptual test than the students who wrote summaries.

Linking Novice-Expert Differences to Cognitive Load Theory

As is apparent from the above mentioned studies, novices and experts can be placed on a continuum of prior knowledge (Cook, 2006), which influences perception and attention (Arcavi, 2003). Learners use prior knowledge to select relevant information from graphics, add information from their prior knowledge, and develop a mental model. Novices have fragmented knowledge, where pieces of information are only weakly connected (Durso & Dattel, 2006). They lack coherent and integrated knowledge, and their understanding is limited to perceptual inputs (surface features) (Wood, 1999). Their mental models do not go beyond the perceptual level of processing; they are not able to easily coordinate features within and across multiple representations to develop an understanding of the underlying concepts (Kozma & Russell, 1997).

In contrast, experts have more domain knowledge in the form of well organized schemas. Thus, they are able to understand important core principles represented by a graphic (Kozma et al, 2000; Stylianou, 2002; Stylianou & Silver, 2004). They can concentrate more on relevant information for constructing an effective mental model (Wood, 1999) and also possess large schemas specific to the domain (Kozma & Russell, 1997). Even when they are exposed to novel information, experts are able to use relevant prior knowledge as a starting point for interpretation (Kohl & Finkelstein, 2008).

The differences in the use of visual representations by experts and novices can be linked to cognitive architecture. According to Cook (2006), cognitive load theory assumes that individuals have a limited working memory and, when overloaded, learning will not take place. Because high intrinsic load of multiple representations exceeds the capacity of working memory, novice learners do not necessarily make use of multiple representations, and usually rely on a familiar or simple one. If switching between representations occurs, the learner has difficulty understanding the representations utilized (Cook, 2006). Because experts have well-developed schemas, they attend to different information than novices: experts link their initial visual and verbal representations to underlying principles of the content, and develop a more comprehensive mental model (Cook, 2006).

The second important implication from the literature review is how the two modes of visualization – from internal to external representations (drawing) and from external to internal representations (analyzing drawings) – have a bearing on cognitive load during learning. This is discussed next.

The Two Modes of Visualizations and Cognitive Load Theory

Understanding and Learning from Visual Representations. According to Scaife and Rogers (1996), among others (Arcavi, 2003; Cook, 2006; Gobert & Clement, 1999), when a diagram is drawn by another person (teacher or author of a textbook) and presented to a learner, the diagram may be used to reduce extraneous cognitive load. Text is linear, diagrams are not. Because of this, more information can be stored in diagrams. For example, the relative positioning of elements is implied in a diagram; or the relationship between the sizes and directions of physical properties can be apparent simply from a scan of the diagram. Moreover, like worked examples, visual representations are said to help in the construction of schemas (Cook, 2006). The ideas are already worked out for the learner, so the learner simply has to analyze the information for schema construction. However, like worked examples, it may be that the diagrams are ignored and not analyzed to the required extent for the learner to acquire the schema.

Similarly, diagrams are said to influence the self-explanation effect (Cox, 1999; Zhang, 1997; Ainsworth & Loizou, 2003). In Ainsworth and Loizou's (2003) study, subjects were presented with text or diagrams on the circulatory system, while prompted to self-explain. The students that had a diagram self-explained more and, more importantly, gained greater conceptual understanding of the circulatory system. However, in this study, students were prompted to self-explain. If students were not prompted, would they use this technique to develop their schemas? Biggs (1999), among others (Pintrich et al. 1993; Weinstein & Palmer, 1990), point to an interesting division among learners: some students are high-elaborators and others are low-elaborators. As previously noted, high-elaborators use the self-explanation effect spontaneously, whereas low-elaborators do not (Biggs, 1999, Pintrich et al. 1993; Weinstein & Palmer, 1990). One might question whether low-elaborating students would use self-explanation in an authentic situation – for instance, when studying from a textbook that included diagrams. Based on theoretical considerations, one might argue that they would not engage in self-explanation. Thus, to benefit from the self-explanation effect, it might be better to engage in the second type of visualization: from internal to external representations. This will be discussed next.

Constructing and using self-generated visual representations. Diagram construction can be seen as a tool to help create mental models (Zhang, 1997, Cox, 1999). Gobert and Clement (1999) demonstrated that by self-generating a diagram after reading a text, learners were more likely to construct a cognitive representation (schema) of the workings of plate tectonics and, consequently, were able to infer more information from their mental model.

If learning from pre-constructed diagrams is like learning from worked examples, then self-constructing diagrams is like learning from completion problems. Recall that completion problems are similar to worked examples, but have key elements missing from those examples. Students must fill in these key elements, which requires them to analyze the worked examples in detail to understand what is missing (Sweller et al., 1998). Asking a student to construct a diagram from scratch is similar to requiring the student to do a completion problem. The student is more likely to process pertinent information in the diagram, thereby fostering schema construction. Moreover, when students draw diagrams, they may use the self-explanation effect more often. To create a diagram from scratch, the learner must first understand the concept to make it concrete (Scaife and Rogers, 1996). The process of constructing the diagram requires the learner to make decisions about the concept and about the diagram. This might lead to a spontaneous self-explanation process, which in turn leads to greater schema production. Accordingly, I predict that students increase their germane cognitive load when constructing their own diagrams.

With respect to learners' prior knowledge, learning by constructing diagrams might also be more beneficial compared to learning from pre-constructed diagrams. Students with low prior knowledge may not understand everything from a pre-constructed diagram. In contrast, if asked to construct a diagram, students with low prior knowledge may not be confused by their own representations. They may draw according to their schema configuration (whether it is correct or not) whereas students with higher prior knowledge may use their own more sophisticated schemas to construct the diagram.

In summary, based on these theoretical considerations, I predict that using visual diagrams for learning will reduce extraneous cognitive load, thus lowering mental effort. Also, I expect that learning by constructing diagrams would increase mental effort, as germane cognitive load would increase. However, learning by constructing diagrams may produce better schema construction than learning from a pre-constructed diagram, which may lead to higher rates of transfer.

The Current Study

Addressing Gaps in the Literature

Stylianou (2002) explains visualization as the fundamental link between external representations and internal knowledge. The visualization process is either the translation from internal to external representations (e.g., learning by self-constructing diagrams) or from external representations to internal ones (e.g., learning with pre-constructed diagrams). Many studies in the field of visual representations have examined the internalization process (Kozma & Russel, 1997; Kozma et al., 2000; Wood, 1999) or the externalization process (Hsieh & Cifuentes, 2003; Kohl & Finkelstein, 2008; Parnafes, 2009; Stylianou, 2002; Stylianou & Silver, 2004). Also, many studies have compared text versus diagrams as two methods of externalizing or internalizing knowledge (Ainsworth & Loizou, 2003; Edens & Potter, 2001; Gobert & Clement, 1999; Jucks et al., 2007). However, to my knowledge, no studies have examined the relationship between the two modes of visualization based solely on the notion of diagrams, i.e. drawing versus analyzing diagrams. Specifically, the current study compares the two modes of visualization, as proposed by Stylianou (2002).

Another gap in the visual representation literature is the lack of a consistent theoretical foundation for the predictions and results found in the studies. To address this, Cook (2006) suggests an approach based on cognitive load theory with an emphasis on prior knowledge. Cook explains that cognitive architecture alone is not the only factor to be considered; individual differences, especially prior knowledge, are critical in determining what impact a visual representation will have on learners' cognitive structures and processes. Prior knowledge can determine the ease with which learners can perceive and interpret visual representations in working memory. The current study adopts Cook's recommended theoretical lens and tests some of the premises that are described in his theory, such as testing ease of learning with diagrams (mental effort) and individual differences of learners (elaboration strategies and prior knowledge).

Finally, Cook's (2006) review of studies on visual representations in science education and cognitive load theory indicates a lack of studies done in authentic settings, such as science classrooms. He states that, "more work is needed to validate instructional design heuristics in the science classroom with diverse, younger populations" (p. 1088). To address this, this study was conducted in participants' science classrooms during their regular science class. Consequently, this study responds to three major gaps in the current literature on visual representations.

Statement of the Problem and Hypotheses

The purpose of this study is to compare learning from a pre-constructed visual representation to learning by self-constructing visual representations. The overarching research question is: Given students' prior knowledge and use of elaboration strategies, what is the preferred method of learning with diagrams: by translating a text into a visual representation or by internalizing pre-constructed diagrams? More specifically: 1. What effects does the diagram condition (learning with pre-constructed diagrams versus learning by self-constructing diagrams) have on mental effort, achievement, and transfer? 2. Do high versus low elaborating students learn better (measured by mental effort, post-test results, and a transfer question) from pre-constructed versus self-constructed diagrams?

3. Do students with low prior knowledge versus high prior knowledge learn better (measured with mental effort, post-test results, and a transfer question) from pre-constructed diagrams or by self-constructing diagrams?

To respond to these questions, students' use of elaboration strategies and prior knowledge of how airplanes fly were collected. Students were then asked to draw diagrams to learn about how airplanes fly or to learn from pre-constructed diagrams. During learning, students' mental effort was measured. Finally, a posttest was administered wherein students were given questions directly related to the learning text (similar task) as well as one transfer question, which asked students to apply what they learned to another context not related to flight.

Based on cognitive load theory related to visual representations, I propose the following hypotheses:

1. Students learning from pre-constructed diagrams will exhibit low mental effort, high performance on a similar task, but low performance on a transfer task. On the other hand, students learning by self-constructing diagrams will exhibit higher mental effort (due to higher germane cognitive load), high performance on a similar task, and high performance on a transfer task (see Table 1) (i.e., main effects for diagram condition on mental effort and transfer but not on similar task performance).

Table 1.

Hypothesis of Mental Effort, Performance on Similar Task, and Performance on Transfer Task, as a Function of Diagram Condition.

	Diagram Condition	
	Pre-Constructed	Self-Constructed
Mental Effort	Low	High
Similar Task	High	High
Transfer Task	Low	High

2. In general, students who use the self-explanation strategy spontaneously (high elaborators) will have higher performance on the posttests compared to low elaborating students (i.e., a main effect for elaboration). Specifically for high elaborating students, the construction of diagrams versus learning from pre-constructed diagrams will yield no difference on both tasks. However, for the low elaborators, learning by self-constructing diagrams will yield better learning of the similar task and transfer task compared to learning from pre-constructed diagrams (see Table 2) (i.e., an interaction between diagram condition and elaboration).

Table 2.

Hypothesis of Performance on Elaboration and Diagram Condition.

	Diagram Condition	
	Pre-Constructed	Self-Constructed
Low Elaboration	Low	Moderate
High Elaboration	High	High

3. Overall, I predict that students with high prior knowledge will have lower mental effort and will outperform low prior knowledge students on the posttest for both the similar task and transfer task (i.e., a main effect of prior knowledge on similar and transfer tasks). In addition, for low-prior knowledge students, learning by self-constructing diagrams will yield better learning performance (for both types of tasks) compared to learning from pre-constructed diagrams. In contrast, for high-prior knowledge students, learning by self-constructing diagrams will yield no difference (i.e., an interaction effect between prior knowledge and diagram condition). This is summarized in Table 3.

Table 3.

Hypothesis of Performance on Prior Knowledge and Diagram Condition.

	Diagram Condition	
	Pre-Constructed	Self-Constructed
Low Prior Knowledge	Low	Moderate
High Prior Knowledge	High	High

Methodology

Participants

One hundred eighty seven grade seven and eight students (97 from grade seven) participated in this study. Of the 187 students, 115 were male and 129 students spoke English as their first language. The students ranged from 12 to 15 years old (M = 12.94, SD = 0.70), and were attending a private English high school near Montreal, Canada.

Materials

Elaboration Strategies. Students' use of elaborative learning strategies was measured using a 5-point, 11-item scale adapted from the Learning and Study Strategies Inventory-High School version (LASSI-HS, Weinstein & Palmer, 1990) (see Appendix A). The 11 items were taken directly from the information processing subscale of the LASSI-HS. Students' scores on this scale measure whether they can create imaginal and verbal elaborations and organizations to foster understanding and recall (Weinstein & Palmer, 1990). For instance, students were asked to rate the statement: "I try to find connections between what I am studying and my own experiences" on a scale from 1 (not at all like me) to 5 (very much like me).

Prior Knowledge. To test their prior knowledge, students were given an open-ended question that asked them to write everything they knew about how airplanes fly (see Appendix B). Specifically, the students were asked: "Explain how airplanes fly. Be very specific. If you want, you can use diagrams and examples in your explanation."

Learning Text. A text from Plane Math was adapted that describes how airplanes fly, which includes an online activity designed in collaboration with NASA (www.infouse.com/planemath) (see Appendix C). This short expository text (approximately 400 words) about flight was separated into ten pages. Each page had one or two sentences explaining some aspect of the phenomenon of flight. There were two versions of this learning text. One version, designed for the first experimental group, did not include diagrams, and instead had big blank boxes embedded below the text. These boxes were meant to serve as a reminder for the students to draw diagrams within them. The second version, intended for the second experimental group, had diagrams provided along with the text on each page in the same location as the box for the first group.

Mental Effort. To measure mental effort, a subjective rating scale was used similar to the one by Ayers (2006). Specifically, at the bottom of each page of the learning text, participants were asked to rate their mental effort. That is, they were asked: "How easy or difficult did you find the concepts on this page?" The rating consisted of a 7-point scale ranging from 1 (extremely easy) through 4 (moderate) to 7 (extremely difficult).

Achievement. To test their understanding of how planes fly, a posttest was administered (see Appendix D). This posttest included one open ended question that was identical to the pretest question. This was intended to estimate participants' final qualitative mental model. In addition, the posttest included four multiple choice test questions assessing the content area that was described directly in the learning text. For example, one question asked: "Plane A is smaller and weighs less than plane B. How much lift will Plane B need to get off the ground? a) same as A, b) more than A, c) less than A." Finally, the posttest included a transfer question that required a deeper understanding of Bernoulli's principle (i.e., a constructed schema of this principle): "A roof is lifted off a building during a severe windstorm. Why does this happen? Be specific. You can use diagrams and examples in your explanation."

Procedure

Each student was randomly assigned to one of two groups: learning by self-constructing diagrams (90 students) and learning from pre-constructed diagrams (96 students). Students first completed a short demographics questionnaire along with the elaboration strategies questionnaire. On a later day, during their regular science class, each student completed the prior knowledge test. Next, each participant was given a short expository text about flight and were told that they would be given a test on the material they were about to learn.. The diagram construction group did not have any diagrams embedded in their text. Rather, the participants in this group were instructed to carefully create a diagram depicting the concepts contained in the text on each page. In contrast, the second group was provided with a diagram along with the text on each page. This experimental group was instructed to carefully inspect and understand each drawing. After reading each page, both groups were asked to rate their mental effort required for the task.

Once students finished reading the text they were given a posttest that contained six questions: The first question was a duplication of the pretest mental model question. The next four were multiple choice questions, which tested the participants' basic understanding of the concepts given in the text. The final question was a transfer question to assess whether students could apply the information in a different context. The procedure is summarized in Figure 1.

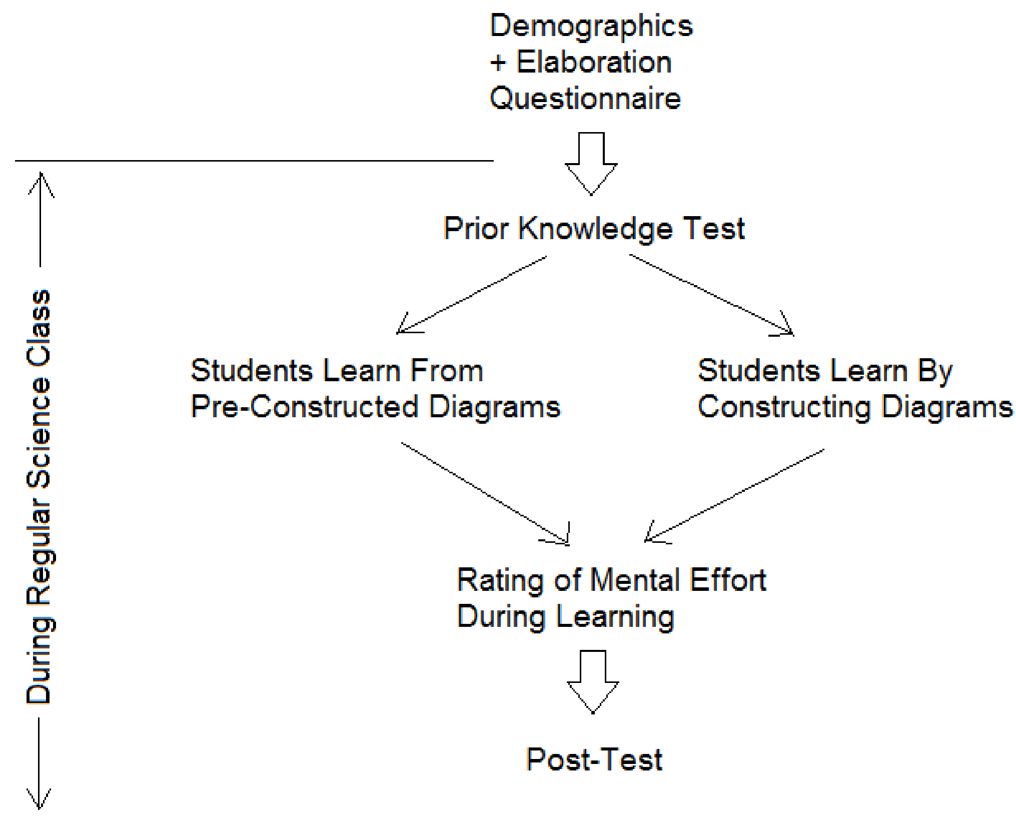


Figure 1. Flow chart of activities during the study.

Scoring

Elaboration Score. Prior to starting the study, students completed an adapted version of the LASSI-HS to assess their use of elaborative learning strategies. The range of possible scores was from 11 (low elaborating student) to 55 (high elaborating student). For students in this study, the actual range of scores was from 17 to 50 (Median = 34, M = 34.05, SD = 6.31). The coefficient alpha for this subscale is 0.63. To compare low to high elaborating students, a median split was used wherein students were considered high elaborating if their score was 34 or higher, and low elaborating students if their score was lower than 34. This resulted in 94 high elaborating students and 92 low elaborating students.

Pretest. The prior knowledge test was scored out of 3. Since the prior knowledge test was a qualitative measure of their initial mental model, answers were rated on a scale from 0 (no idea how planes fly) to 3 (a complete picture and good understanding of the basics of how airplanes fly). See Table 4 for a detailed prior knowledge mental model rating scheme, along with the frequencies of the four possible mental models. In subsequent analyses, because there were only five students who had high initial mental models (with a score of 3), and only 22 students with a moderately high mental model (score of 2), students with a score of 1 through 3 were grouped together. Therefore, the two prior knowledge groups consisted of 52 low prior knowledge and 135 higher prior knowledge students.

Table 4.

Mental Model Score (MM), Description, and Prior Knowledge Frequencies.

MM	Description	Pretest Frequency
0	Low Qualitative Mental Model: • The student has no idea how an airplane flies.	52
1	Moderately Low Qualitative Mental Model: • The student wrote things like: • An airplane uses its wings to fly. • They need to go very fast. • Planes need to be very light. • Planes use turbines to catch the wind.	108
2	Moderately High Qualitative Mental Model: • If the student wrote about forces, lift, or air pressure, however did not explain these fully, or made obvious mistakes in their reasoning. • E.g. "Air pushes up the wings of the airplane."	22
3	High Qualitative Mental Model: • If the student explained lift correctly and fully, with a discussion of air pressure.	5

Mental Effort. During the learning stage, students were randomly assigned to the pre-constructed diagram condition or the diagram construction condition. In the pre-constructed diagram condition, students had access to both text and diagrams. But in the drawing condition, students drew diagrams of the given text (See Figure 2 for an example). At the end of each page, students were asked to rate their mental effort. A total score for mental effort was calculated, with a possible range from 10 (lowest possible mental effort) to 70 (highest possible mental effort). In this study, the range was 10 to 65.

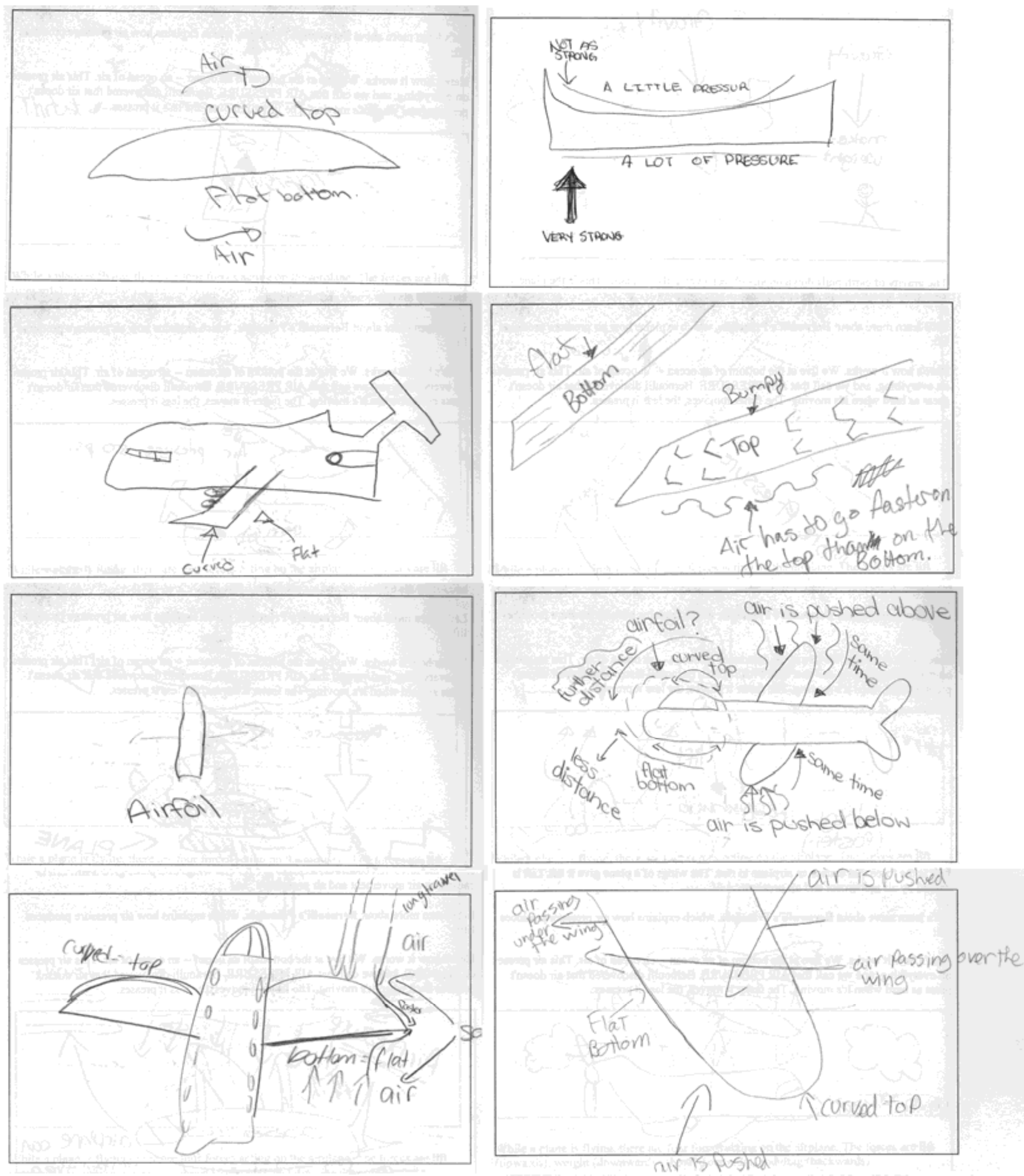


Figure 2. A sample of student diagrams for the statement: “The cross-section of a wing has a curved top and flat bottom – this shape is called airfoil.”

Posttest. There were three parts to the posttest. The first part was the same question as the pretest. This was used to measure the participants’ final qualitative mental model. The scoring followed the same scheme as the pretest, from 0 to 3 (see Table 4 for a description). The second part of the posttest was made up of four multiple choice test questions related to the "How Planes Fly" text. Each answer was scored 0 (incorrect) or 1 (correct), for a maximum score of 4.

The final posttest section was a transfer question, where Bernoulli's principle was to be applied to a non-airplane context. This was an open-ended question, similar to the pretest and posttest mental model questions. This question was scored on a similar scale as the two mental model questions, where 0 represented a completely incorrect explanation and 3 represented a completely correct response. Table 5 summarizes the overall means and standard deviations (collapsed across groups) for all three sections of the posttest in addition to the mental effort score.

Table 5.

Mean and Standard Deviations for Mental Effort, Posttest Mental Model, Multiple Choice, and Transfer Questions.

Dependent Variables	M	SD
Mental Effort (out of 70)	28.85	10.92
Posttest Mental Model (out of 3)	2.37	.67
Multiple Choice (out of 4)	3.35	.93
Transfer Question (out of 3)	1.44	1.08

Independent and Dependent Variables

In this 2 x 2 x 2 design, the independent variables included the experimental group (i.e. self-generated visual representations versus pre-constructed visual representations group), whether students were high or low elaborators, and prior knowledge (low versus higher prior knowledge). The dependent variables were the results on each of the posttests, as well as the subjective measure of mental effort.

Results

Preliminary Analyses

To ensure equivalence between the two diagram condition groups on prior knowledge, a t-test was performed. Results revealed the two groups were not significantly different ($t\ (185) = 0.659$, $p = 0.511$), with the diagram construction condition having a mean initial mental model score of 0.74 out of a possible score of 2 (SD = 0.44) and the pre-constructed diagram condition having a mean initial mental model score of 0.70 (SD = 0.46).

Similarly, the two diagram condition groups were equivalent in terms of elaboration strategies. A t-test revealed no significant differences between the two groups ($t(185) = -.783$, $p = .435$), with the diagram construction condition having a mean elaboration score of 33.68 out of a possible score of 55 (SD = 6.47) and the pre-constructed diagram condition having a mean elaboration score of 34.31 (SD = 6.16).

Main Analyses

Correlations. The correlations between the dependent variables were considered to be in the low range (see Table 6 for the correlation matrix). Therefore, instead of a multivariate analysis of variance, separate analyses were performed for each dependent variable (to increase power). The four dependent variables were mental effort, posttest mental model, total multiple choice score, and the transfer question score.

Table 6.

Correlations Between the Dependent Variables.

	1	2	3
[1]Mental Effort			
[2]Posttest Mental Model	-.42**		
[3]Multiple Choice	-.22**	.40**	
[4]Transfer Question	-.32**	.45**	.27**

Note. ** denotes $p < .01$. Superscript numbers beside variables in first column are the same variables (numbered) in first row.

Mental effort. The analysis of variance (ANOVA) revealed a significant main effect for diagram condition ($F(1, 178) = 7.55$, $p = 0.007$, $\eta^2 = 0.04$) and a significant interaction between elaboration and prior knowledge ($F(1, 178) = 11.565$, $p = 0.001$, $\eta^2 = 0.06$). No other significant results were found. Table 7a summarizes the means and standard deviations for mental effort as a function of group.

Table 7a.

Means (and Standard Deviations) of Mental Effort as a Function of Diagram Condition, Elaboration, and Prior Knowledge.

		Diagram Condition	
Elaboration	Prior Knowledge	Self-Constructing	Pre-Constructed
Low	Low	28.87 (12.55)	27.27 (8.04)
	Higher	34.94 (12.07)	26.66 (9.21)
High	Low	37.88 (7.24)	31.50 (8.58)
	Higher	27.03 (12.14)	24.26 (8.42)

The significant main effect for diagram condition demonstrates that mental effort was higher for students in the drawing condition compared to students with access to pre-constructed diagrams ($M = 26.48$, $SD = 8.83$). This result answers part of the first research question and supports the hypothesis that students in the self-constructing diagram condition will have a higher mental effort. On the other hand, the significant interaction between prior knowledge and elaboration score has no direct relevance to this study; therefore, it will not be analyzed any further.

Posttest mental model. The ANOVA revealed a significant main effect for prior knowledge ($F(1, 179) = 5.02$, $p = 0.026$, $\eta^2 = 0.03$), and two significant interactions between diagram condition and prior knowledge ($F(1, 179) = 5.37$, $p = 0.018$, $\eta^2 = 0.03$) and elaboration and prior knowledge ($F(1, 179) = 6.81$, $p = 0.010$, $\eta^2 = 0.04$). No other significant results were found. Table 7b summarizes the means and standard deviations of the posttest mental model as a function of independent variables.

Table 7b.

Means (and Standard Deviations) of the Posttest Mental Model as a Function of Diagram Condition, Elaboration, and Prior Knowledge.

		Diagram Condition	
Elaboration	Prior Knowledge	Self-Constructing	Pre-Constructed
Low	Low	2.40 (.63)	2.20 (.77)
	Higher	2.06 (.68)	2.46 (.51)
High	Low	2.25 (.71)	1.93 (1.00)
	Higher	2.56 (.56)	2.65 (.48)

The significant main effect for prior knowledge demonstrates that students with low prior knowledge achieved lower posttest mental models ($M = 2.19$, $SD = 0.79$) compared to students with higher prior knowledge ($M = 2.44$, $SD = 0.61$). This result addressed the third research question and supports the hypothesis that students with lower prior knowledge will have lower posttest results as opposed to their higher prior knowledge counterparts.

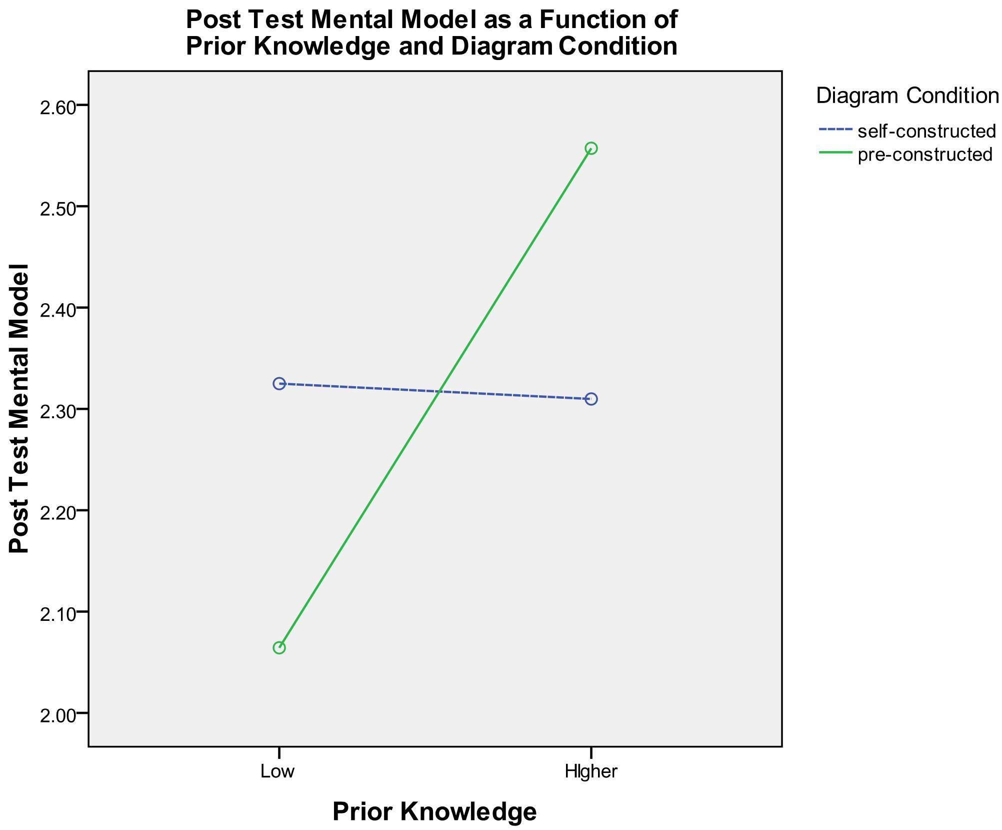


Figure 3. Posttest mental model as a function of prior knowledge and diagram condition.

To further explore the interactions (see Figure 3), a post hoc analysis was run using Fisher's least significant difference procedure (LSD) to control for Type I errors. This analysis revealed a significant difference between the two diagram conditions for high prior knowledge (mean difference = -0.28, SE = 0.11, p = 0.015) and a significant difference between low and high prior knowledge for the pre-constructed diagram condition (mean difference = -0.50, SE = 0.14, p = 0.001). The other two comparisons were not significant. These results suggest that for students with high prior knowledge, the pre-constructed diagram condition produced better posttest mental models than for the self-constructing diagram condition, but for the low prior knowledge students, there was no difference in diagram condition. Moreover, for the pre-constructed diagram condition, students with low prior knowledge had significantly lower posttest mental models than students with high prior knowledge, but there was no such difference for the self-constructing diagram condition. These results address the third research question and supports the hypothesis that the drawing condition was beneficial for low prior knowledge students, but not for the high prior knowledge students. Conversely, the pre-constructed diagram condition was beneficial for the high prior knowledge students but not for the low prior knowledge students.

Similar to the mental effort results, the significant interaction between pretest mental model and elaboration has no direct relevance to this study. It does not address any of the research questions; therefore, it will not be discussed further.

Multiple Choice Score. The ANOVA revealed a significant main effect for prior knowledge ($F(1, 178) = 4.49$, $p = 0.035$, $\eta^2 = 0.03$), but no other significant results were found. Table 7c summarizes the means and standard deviations of the multiple choice score as a function of group.

Table 7c.

Means (and Standard Deviations) of Multiple Choice Score as a Function of Diagram Condition, Elaboration, and Prior Knowledge.

		Diagram Condition	
Elaboration	Prior Knowledge	Self-Constructing	Pre-Constructed
Low	Low	2.93 (1.39)	3.36 (.74)
	Higher	3.20 (1.02)	3.68 (.48)
High	Low	3.12 (.99)	3.07 (1.07)
	Higher	3.38 (.94)	3.55 (.81)

The significant main effect for prior knowledge shows that students with low prior knowledge performed worse on the multiple choice test ($M = 3.12$, $SD = 1.07$) compared to higher prior knowledge students ($M = 3.44$, $SD = 0.56$). Again, this result supports the hypothesis that students with lower prior knowledge will have lower posttest results as opposed to their high prior knowledge counterparts.

Transfer Question. Finally, for the transfer question, results from the ANOVA demonstrated no significant main effects or interactions. Table 7d summarizes the means and standard deviations of transfer question score as a function of group.

Table 7d.

Means (and Standard Deviations) of Transfer Question Score as a Function of Diagram Condition, Elaboration, and Prior Knowledge.

		Diagram Condition	
Elaboration	Prior Knowledge	Self-Constructing	Pre-Constructed
Low	Low	1.40 (1.06)	1.79 (1.12)
	Higher	1.14 (.94)	1.50 (1.14)
High	Low	1.50 (1.07)	0.93 (1.27)
	Higher	1.34 (1.00)	1.83 (1.08)

Summary of Results

Research Question 1. The first research question sought to determine how the two conditions, self-constructed versus pre-constructed diagrams, differed on the dependent variables of mental effort, posttest mental model, multiple choice score, and transfer question score. The main effects of diagram condition from the above four analyses addressed this question. As predicted, mental effort was significantly greater for the self-constructing diagram condition compared to the pre-constructed diagram condition. No difference was predicted between the two groups for performance on a similar task. The performance on a similar task was measured using two variables: posttest mental model and multiple choice total score. In support of this hypothesis, neither variable differed significantly between the two groups. Finally, performance on a transfer task was hypothesized to be better for the self-constructing diagram condition. This was not corroborated by the results. In fact, although not significant, the opposite effect was observed: participants in the self-constructing diagram condition had a lower mean transfer question score (M = 1.29, SD = 0.99) than the participants in the pre-constructed diagram condition (M = 1.59, SD = 1.16).

Research Question 2. The second research question addressed whether high versus low elaborating students learned differently in the pre-constructed versus self-constructing diagram conditions. Results revealed no significant main effects on the elaboration variable, therefore the assumption that high elaborating students will learn better than low elaborating students was not supported. Moreover, there was no significant interaction between elaboration and diagram condition, which contradicts the hypothesis that low elaborating students will do better in the self-constructing diagram condition.

Research Question 3. The third research question assessed whether students with high versus low prior knowledge learned differently in the pre-constructed versus self-constructing diagram conditions. The first hypothesis was that students with low prior knowledge would exhibit higher mental effort than students with low prior knowledge. This was not confirmed as there was no significant main effect for prior knowledge on mental effort. The next hypothesis for this research question was that students with high prior knowledge would outperform their counterparts on the posttest. This was confirmed on the posttest mental model and performance on the multiple choice questions. Results revealed a significant main effect for prior knowledge, with higher prior knowledge students performing significantly better than their lower prior knowledge counterparts.

Finally, the last hypothesis for the third research question was that students with low prior knowledge would benefit from the self-constructing diagram condition and perform better than the low prior knowledge students in the pre-constructed diagram condition. This prediction was supported by the significant interaction between prior knowledge and diagram condition on the posttest mental model variable.

Discussion

The purpose of this study was to compare the effects of two visual representation conditions, prior knowledge, and use of elaboration strategies on various learning outcomes. The first condition used pre-constructed diagrams as part of the visualization process of external representation into internal knowledge. The second condition used self-constructed diagrams to translate the students' internal model of knowledge into external representations. As such, this study was important to advance visual representation research by comparing these two processes of visualization. In addition, students' elaboration strategies and their prior knowledge were considered as important factors in the learning process. The comparison of these two conditions through a lens of cognitive load theory is discussed in the following sections. First, the results are interpreted for each research question. Then, theoretical and education implications are considered. Finally, the limitations of the study and future directions are explored.

Pre-Constructed Diagram versus Self-Constructed Diagram Conditions

The results demonstrated that the posttest mental model was similar for each diagram condition. This implies that, in general, students learned similarly whether they actively drew diagrams or learned from a provided diagram. However, an interaction effect between the diagram conditions and prior knowledge was observed for the posttest mental model. This means that students with lower prior knowledge achieved higher posttest mental models when in the drawing condition, whereas students with higher prior knowledge achieved higher mental models when in the pre-constructed diagram condition. The general result is consistent with Edins and Potter's (2001) study. Similarly to this study, Edins and Potter showed that students in the drawing condition versus the group with access to pre-constructed diagrams did not differ significantly on their final conceptual understanding of the physics concept. However, the results in the current study demonstrate that there needs to be a qualifier of this generalization: some students (i.e. with low prior knowledge) benefit from actively drawing diagrams while learning, whereas other students (i.e., with higher prior knowledge) learn better with pre-constructed diagrams. Clearly, as Cook (2006) suggested, prior knowledge is an important individual difference variable that needs to be taken into consideration.

Second, as predicted, students' metal effort in the self-constructing diagram condition was significantly higher than that of students using pre-constructed diagrams. I hypothesized that this higher mental effort was a function of higher germane cognitive load. That is, if students learned more as a result of drawing diagrams, then this increased mental effort could be caused by higher germane load – learning that occurs while drawing. However, results showed no difference in learning outcomes. Therefore, students' higher mental effort cannot be attributed to germane cognitive load. Instead, this can be attributed to extraneous load.

Paas and van Merrienboer (1994) explain that mental effort and learning outcome measurements can be combined to indicate either extraneous or germane cognitive load. For instance, if high mental effort is coupled with high learning outcomes, then the cognitive load is germane. However, when mental effort is high yet higher learning outcomes are not observed, as in the present study, cognitive load is said to be extraneous. Therefore, using Paas and van Merrienboer's cognitive load measurement technique, this study demonstrated higher extraneous load for the self-constructing diagram condition, but not higher germane cognitive load as was initially anticipated.

As stated above, students in the self-constructing diagram condition had a higher mental effort yet they did not perform better on any of the achievement measures as compared to the pre-constructed diagram condition. In fact, provided diagrams produced higher achievement scores in cases where students had higher prior knowledge, even though that level of prior knowledge was not deemed particularly high. This may be the case because diagrams increase working memory capacity (Sweller, 1994; Sweller et al., 1998) and reduce extraneous cognitive load (Arcavi, 2003; Cook, 2006; Scaife & Rogers, 1996).

Higher working memory capacity. Sweller (1994) explains that working memory has partially independent processors associated with individual sensory modes: visual and auditory. Working memory capacity may be increased by using multiple processors, rather than by a single sensory mode (Cook, 2006; Sweller, 1994; Sweller et al., 1998). This so-called modality effect takes advantage of both visual and auditory inputs occurring simultaneously (Cook, 2006; Sweller et al., 1998), which provides a larger total working memory allowing for more complex learning with higher intrinsic cognitive load and even higher germane cognitive load.

Although students were not provided a narration of the text in this study, they may have used both channels to process the textual and diagrammatic information to increase processing capacity. That is, some studies have confirmed that text can be processed in the auditory as opposed to the visual mode (Baddeley, Gathercole & Papagno, 1998). Results of this study support such a hypothesis. Students with the provided diagram had lower mental effort, which might indicate a higher working memory capacity. Alternatively, as Cook (2006) argues, pre-constructed diagrams may lower extraneous cognitive load. This is considered next.

Lower Extraneaous Cognitive Load. Cook (2006) examined visual representations and how they apply to science learning and instruction. Because many science topics are complex, where numerous interacting elements must be understood simultaneously, Cook states that good science instruction must lower extraneous cognitive load to allow for the higher intrinsic load of the scientific content. Cook concludes that visual representations are essential in science education to lower extraneous cognitive load. Arcavi (2003) explains how diagrams can lower extraneous cognitive load:

> because of a) their two-dimensional and non-linear organization as opposed to the emphasis of the 'printed word' on sequentiality and logical exposition; and b) their grouping together of clusters of information which can be apprehended at once, similarly to how we see in our daily lives, which helps in reducing knowledge search making the data perceptually easy. (p. 218)

Scaife and Rogers (1996) point to yet another explanation of the apparent reduction in extraneous cognitive load when using diagrams: constraining or limiting possibilities. For instance the statement, "The cross-section of a wing has curved top and flat bottom – this shape is called airfoil," can be interpreted in many incorrect ways as was seen by the results from students in the drawing condition (see Figure 2). The pre-constructed diagram condition sets limits to this description, and specifically demonstrates what is meant by this statement, constraining the number of possible interpretations of "curved top and flat bottom," to reduce extraneous cognitive load.

In this study, mental effort decreased and learning increased when a pre-constructed diagram was presented, which supports this explanation. Students having to draw their own diagram were presented with the task of translating text into an internal representation, followed by re-translating this internal representation into a diagram. This seemed to overload their working memory, as demonstrated by their increased mental effort and decreased overall learning.

In summary, it can be said that students in the self-constructing diagram condition had their working memory overloaded preventing at least some of the learning that could have taken place. Students in the pre-constructed diagram condition had fewer working memory demands, higher working memory capacity due to the modality effect, and lower extraneous cognitive load. To explore further and refine the differences of the two diagram conditions, I also examined individual differences and their relationship to each condition. The first individual difference examined in this study was the extent to which elaboration strategies were employed by students and how this related to each diagram condition. Addressing this second research question, the elaboration strategies variable is discussed next.

High versus Low Elaborating Students

The self-explanation effect is important for meaningful learning to take place (Cox, 1999; Zhang, 1997). Ainsworth and Loizou (2003) demonstrated that diagrams as opposed to text are linked with the self-explanation effect. In addition, it has been demonstrated that high-elaborators use the self-explanation effect spontaneously, but low-elaborators do not (Biggs, 1999; Pintrich et al. 1993; Weinstein and Palmer, 1990). Since this study did not specifically prompt students to self-explain while learning, I predicted that students in the pre-constructed diagram condition would learn better if they self-explained spontaneously (i.e. the high elaborators). However, for the self-constructing diagram condition, I predicted that low-elaborating students would perform just as well as the high elaborating students, assuming that drawing diagrams would act as a prompt to self-explain.

The results from this study did not support either of these assumptions. High elaborating students did not outperform low elaborating students on any of the posttest measures. Furthermore, low elaborating students did not significantly differ in their posttest results based on their diagram condition. Therefore, it may be that the influence of diagrams on the self-explanation effect has to do with diagrams in general and not whether they are pre-constructed or self-constructed. However, since I did not actually measure whether students self-explained or not, I can only say that this speculation is plausible given the pattern of results. The other individual difference examined in this study was students' prior knowledge and its relation to the two diagram conditions. This third research question, dealing with prior knowledge of the learner and the diagram condition, is considered next.

High versus Low Prior Knowledge

Prior knowledge is a key consideration when it comes to intrinsic cognitive load. People with high prior knowledge use higher order schemas and therefore do not overload working memory with too many individual elements (Cook, 2006; Sweller, 1994). Students with low prior knowledge, however, have smaller, simpler, more fragmented, and weakly connected schemas (Durso & Dattel, 2006). This study confirms these assertions about the importance of prior knowledge. Students with more prior knowledge achieved significantly higher posttest results.

Moreover, prior knowledge influences perception and attention (Arcavi, 2003). Students with low prior knowledge do not go beyond the perceptual level of processing (Kozma & Russell, 1997). In this regard, low prior knowledge students are not able to easily coordinate features within and across many representations to develop an understanding of the underlying concepts (Kozma & Russell, 1997). Therefore, in this study, I hypothesized that students with low prior knowledge would benefit more from self-constructing diagrams compared to learning from pre-constructed diagrams, as low prior knowledge students might not fully understand the pre-constructed diagrams. If low prior knowledge students had the opportunity to construct diagrams from scratch then they may not be confused by unfamiliar but standard scientific visual representations and could use their own schemata to externalize their knowledge.

Results from this study confirmed this hypothesis. Students with higher prior knowledge demonstrated a significantly higher posttest mental model when they were in the pre-constructed diagram condition compared to the self-constructing diagram condition, whereas the opposite relationship was true for low prior knowledge students. This result indicates that students with low prior knowledge learn better by drawing their own diagrams, whereas students with higher prior knowledge learn better by using a provided standard scientific diagram.

Theoretical Implications

Stylianou (2002) defines visualization as a translation from external to internal representation or vice versa, emphasizing the connection made by the individual between the physical image and the mental image. Even though the visualization process is bi-directional, no studies until now have compared the external-to-internal translation with the internal-to-external translation. The current study filled this gap in the visual representation literature by comparing these two directions in visualization: learning with pre-constructed diagrams versus learning by self-generating diagrams. The comparison between the two modes of visualization was based on how the two conditions affect students' mental effort and achievement, and whether students' elaboration strategies and prior knowledge influence the two conditions.

Moreover, cognitive load theory was used to provide a foundation from which to explain differences between these two visualization processes. That is, by combining the literature on visual representations and cognitive load theory, a better understanding of the two modes of visualization was achieved. For instance, by measuring both mental effort and achievement (Paas & van Merrienboer, 1994), this study observed the type of cognitive load (extraneous or germane) associated with the two conditions. Furthermore, by employing Cook's (2006) theoretical framework, where prior knowledge supplements cognitive load theory, this study was able to refine some important distinctions of the preferred circumstances for each type of visualization. Finally, to address the lack of authentic studies with younger populations (Cook, 2006), this study sampled students from an authentic science classroom setting.

Educational Implications

One educational implication of this study is that pre-constructed diagrams are useful in teaching scientific concepts. They reduce students' mental effort and boost learning. However, pre-constructed diagrams must be used cautiously, as their usefulness depends on the student's prior knowledge (i.e., low prior knowledge students benefit from the self-constructing diagrams, whereas higher prior knowledge students benefit from the pre-constructed diagrams). If students are completely new to a topic, then the teacher's diagram or textbook pictures might be confusing. It therefore might be beneficial to start a new topic by asking students to construct their own diagrams, so that they can access their prior knowledge in constructing new schema. Following this introduction with self-constructed diagrams, teacher-generated or textbook diagrams can be very useful in teaching and explaining scientific concepts, creating mental models which are essential in science education.

Limitations and Future Directions

One major limitation of this study was the inability to measure some of the key variables directly. For instance, to measure the type of cognitive load used by students in each condition, self-reported mental effort and achievement was combined to determine whether the cognitive load was germane or extraneous (Paas & van Merrienboer, 1994). Recently, DeLeeuw and Mayer (2008) attempted to match various measurements methods of cognitive load (i.e., response time to secondary task, subjective effort rating, and subjective difficulty rating) with the three types of cognitive load (i.e., extraneous, intrinsic, and germane, respectively). Although still in their infancy, DeLeeuw's and Mayer's measurement techniques may more directly measure which type of cognitive load is actually being used. Therefore, this measurement method could potentially be applied in future studies to confirm the assertion that the self-constructing diagram condition increases extraneous cognitive load.

Another important variable, the self-explanation effect, was also measured indirectly. That is, students self-reported on their elaboration strategies, and the score on the self-reported questionnaire was considered as an indirect measure of whether students would self-explain spontaneously or not. Also, students' achievement on the posttest was considered evidence for the use of the self-explanation effect. However, it would have been more accurate to measure whether students in one condition self-explained more versus the other condition. Therefore, a comparison study of the two visualization processes and whether the self-explanation effect is influenced by the condition would be an important next step in visual representations research.

Third, there is always the possibility that prior knowledge and posttest learning was not accurately measured. There was a difficulty in determining how the mental model changed. The students seemed to be excited and interested initially, writing long statements for the pre-test mental model. However, after the learning text, especially if they were in the drawing condition, they seemed fatigued or anxious to finish the posttest and may not have been as careful and complete in their responses. This might have resulted in an underestimation of the posttest mental model, biased against students in the drawing condition. A way to resolve this issue would be to do a post interview with the students to explore further how their mental models changed and whether they felt that diagram construction was difficult and/or beneficial.

There were a few other implications, which were not considered initially. First, the time spent by students in both conditions was inconsistent: Students took much less time while learning from pre-constructed diagrams as opposed to the self-constructing diagram condition. This speaks to cognitive load being higher for those students who had to construct their diagrams, and supports the theory that the drawing condition increased extrinsic cognitive load. As this appears to be relevant, yet was not considered initially as a potential factor, it would be interesting to include time as a dependent variable in a future study comparing the two visualization processes.

Finally, it might be that this content was too complex for these instructional methods to be effective. Other studies should consider simpler concepts to examine whether task complexity influences these outcomes. Another implication might be that students are unskilled or inefficient at producing helpful self-generated visual representations. Different results may be seen if students are trained to draw useful diagrams (Hsieh & Cifuentes, 2003; Parnafes, 2009).

Conclusion

This study examined the instructional method of drawing as a learning process to induce germane cognitive load. The study confirmed some of the hypotheses and refuted others. In general, the results support the notion that prior knowledge has a significant impact on learning. Also, in this learning context with this content, when students have low prior knowledge, they seem to learn better by self-constructing diagrams instead of learning from standard scientific diagrams. However, with higher prior knowledge this trend is reversed and students tend to learn better from pre-constructed diagrams.

Whether a student uses elaboration strategies or not seemed to have no effect on whether students learn better from pre-constructed diagrams or from self-constructing diagrams. Finally, it appears that there is some evidence pointing to a cognitive overload that prevents learning in the drawing condition. Although mental effort increased for the drawing condition, this did not appear to be germane cognitive load, as students did not learn more by drawing.

Acknowledgements

I would like to thank Dr. Krista Muis for her constructive criticism and inspiring comments on the thesis. Also, great thanks go out to Kirsten Wallace, Lawrence Harris, and Gregor Tedford, the three science teachers that allowed me to take over their classrooms for the duration of the study. Also, I would like to thank Susan Stoddard of Plane Math for allowing me to use her text on how airplanes fly in my study, and Amel Irbah for translating the abstract into French. Finally, I would like to thank my husband Alex Gierus and my three children, Jakub, Robert, and Konrad for giving me the inspiration and time to work on this thesis.

I dedicate this thesis to my best friend Jenny Chao. She was the one that initially inspired me to pursue a Masters – without her push, this endeavour would have never begun.

References

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

Arcavi, A. (2003). The Role of Visual Representation in the Learning of Mathematics. *Educational Studies in Mathematics*, 52, 215-241.

Ayers, P. (2006). Using Subjective Measures to Detect Variations of Intrinsic Cognitive Load within Problems. *Learning and Instruction,* 16(5), 389-400.

Baddeley, A. (1992). Working memory. *Science* 255: 556-559.

Baddeley, A., Gathercole, S., & Papagno, C.(1998). The phonological loop as a language learning device. *Psychological Review*, 105(1), 158-173.

Biggs, J. (1999). What the Student Does: Teaching for Enhanced Learning. *Higher Education Research Development,* 18(1), 57-75.

Bruer, J. (1994). *Schools for Thought: A Science of Learning in the Classroom*, Cambridge, Massachusetts: The MIT Press.

Cook, M. (2006). Visual Representations in Science Education: The Influence of Prior Knowledge and Cognitive Load Theory on Instructional Design Principles. *Science Education,* 6, 1073-1091.

Cox, R. (1999). Representation construction, externalised cognition and individual differences. *Learning and Instruction*, 9, 343-363.

Chandler, P., & Sweller, J. (1992). "The split-attention effect as a factor in the design of instruction". *British Journal of Educational Psychology* **62**: 233–246.

DeLeeuw, K. E. & Mayer, R. E. (2008). A Comparison of Three Measures of Cognitive Load: Evidence for Separable Measures of Intrinsic, Extraneous , and Germane Load. *Journal of Educational Psychology,* 100(1), 223-234.

diSessa, A.A. (2004). Metarepresentation: Native Competence and Targets for Instruction. *Cognition and Instruction,* 22(3), 293-331.

Durso, F. & Dattel, A. (2006) Expertise and Transportation. In K.A. Ericsson, N. Charness, P. Feltovich, &R. Hoffman (Eds.), *The Cambridge Handbook of Expertise and Expert Performance* (pp.355-372). New York, NY: Cambridge University Press.

Edins, K., M., & Potter, E., F. (2001). Promoting Conceptual Understanding Through Pictorial Representation. *Studies in Art Education*, 42(3), 214-233.

Ellis, H. C. (1965). *The Transfer of Learning*. New York: The Macmillan Company.

Gobert, J. & Clement, J. (1999). Effects of Student-Generated Diagrams versus Student-Generated Summaries on Conceptual Understanding of Causal and Dynamic Knowledge in Plate Tectonics. *Journal of Research in Science Teaching*, 36(1), 39-53.

Hoffman, B. & Schraw, G. (2009). The Influence of Self-Efficacy and Working Memory Capacity on Problem-Solving Efficiency. *Learning and Individual Differences,* 19(1), 91-100.

Hsieh, Y.C.J. & Cifuentes, L. (2003). The Effect of the Use of Student-Generated Visualization as a Study Strategy for Middle School Science Concept

Learning. In C. Crawford et al. (Eds.), *Proceedings of Society for Information Technology & Teacher Education International Conference 2003* (pp. 2998-3005). Chesapeake, VA: AACE.

Jucks, R., Bromme, R., & Runde, A. (2007). Explaining with nonshared illustrations: How they constrain explanations. *Learning and Instruction*, 17, 204-218.

Kohl, P. & Finkelstein, N. (2008). Patterns of multiple representation use by experts and novices during physics problem solving. *Physical Review Special Topics – Physics Education Research*, 4, 010111.

Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The Roles of Representations and Tools in the Chemistry Laboratory and Their Implications for Chemistry Learning. *The Journal of The Learning Sciences,* 9(2), 105-143.

Kozma, R. & Russell, J. (1997). Multimedia and Understanding: Expert and Novice Responses to Different Representations of Chemical Phenomena. *Journal of Research in Science Teaching*, 34(9), 949-968.

Parnafes, O. (2009). Self-Generated Representations (SGR) for Promoting Conceptual Understanding. In Y. Eshet-Alkalai, A. Caspi, S. Eden, N. Geri, Y. Yair (Eds.), *Proceedings of the Chais conference on instructional technologies research 2009: Learning in the technological era.* Raanana: The Open University of Israel.

Pintrich, P. R., Smith, D. A. F., Garcia, T., & McKeachie, W. J. (1993). A manual for the use of the motivated strategies for learning questionnaire. Ann Arbor, MI: University of Michigan.

Paas, F. G. W. C. & Van merrienboer, J. J. G. (1994). Measurement of cognitive load in instructional research. *Perceptual and Motor Skills,* 79(1), 419-430.

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

Selfe, L. (1985). Anomalous drawing development: some clinical studies. In N.H. Freeman & M.V. Cox (Eds.) *Visual Order* (pp. 135-153). New York, NY: Cambridge University Press.

Stylianou, D. (2002). On the interaction of visualization and analysis: the negotiation of a visual representation in expert problem solving. *Journal of Mathematical Behaviour,* 21, 303-317.

Stylianou, D. & Silver, E. (2004). The Role of Visual Representations in Advance Mathematical Problem Solving: an Examination of Expert-Novice Similarities and Differences. *Mathematical Thinking and Learning*, 6(4), 353-387.

Sweller, J. (1988). Cognitive load during problem solving: Effects on Learning. *Cognitive Science* **12** (2): 257–285.

Sweller, J. (1994). Cognitive Load Theory, Learning Difficulty, and Instructional Design. *Learning and Instruction, 4*: 295-312.

Sweller, J., Van Merriënboer, J., & Paas, F. (1998). Cognitive architecture and instructional design. *Educational Psychology Review* **10**: 251–296.

van Merrienboer, J. Kester, L. & Paas, F. (2006). Teaching Complex Rather Than Simple Tasks: Balancing Intrinsic and Germane Load to Enhance Transfer of Learning. *Applied Cognitive Psychology,* 20, 343-352.

van Merrienboer, J. & Sweller, J. (2005). Cognitive Load Theory and Complex Learning: Recent Developments and Future Directions. *Educational Psychology Review 17(2)*: 147-148.

Weinstein, C. E. & Palmer, D. R. (1990) Learning and Study Strategies Inventory – High School Version (LASSI – HS). *H & H Publishing Company, Inc. Clearlwater FL.*

Wierwille, W. W. & Eggemeier, F. T. (1993). Recommendations for Mental Workload Measurement in a Test and Evaluation Environment. *The Journal of the Human Factors and Ergonomics Society,* 35 (2), 263-281.

Wood, B. (1999). Visual Expertise. *Radiology*, 211, 1-3.

Zhang J. (1999). The Nature of External Representations in Problem Solving. *Cognitive Science,* 21(2), 179-217.

Appendices

Appendix A – Measuring High or Low Elaborating Students

LASSI – HS Subscale on Elaboration (Information Processing): questions #12, 15, 23, 27, 32, 39, 46, 49, 52, 63, 75 (Weinstein and Palmer, 1990). Questions were answered on a 5 point scale, from 1 (not at all true of me) to 5 (very true of me).

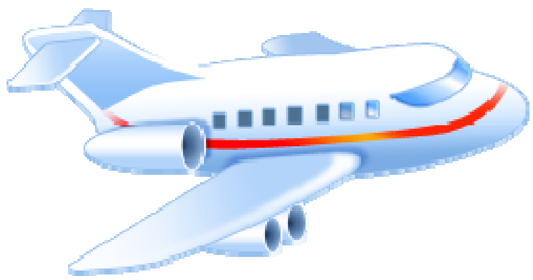
12. I try to think through a topic and decide what I am supposed to learn from it rather than just read it over when doing schoolwork.
15. I learn new words or ideas by imagining a situation in which they occur.
23. I have trouble summarizing what I have just heard in class or read in a textbook.
27. I change the material I am studying into my own words.
32. When I study a topic I try to make the ideas fit together and make sense.
39. I try to find connections between what I am studying and my own experiences.
46. I try to find connections between what I am learning and what I already know.
49. I make drawings or sketches to help me understand what I am studying.
52. I make simple charts, diagrams, or tables to pull together material in my classes.
63. I memorize grammatical rules, technical terms, formulas, etc., without understanding them.
75. I try to make connections between various ideas in what I am studying.

Appendix B – Pretest

Explain how airplanes fly. Be very specific. If you want, you can use diagrams and examples in your explanation.

Appendix C - Learning Text (With Diagrams and Without Diagrams)

How Airplanes Fly



Name: ___________________________________

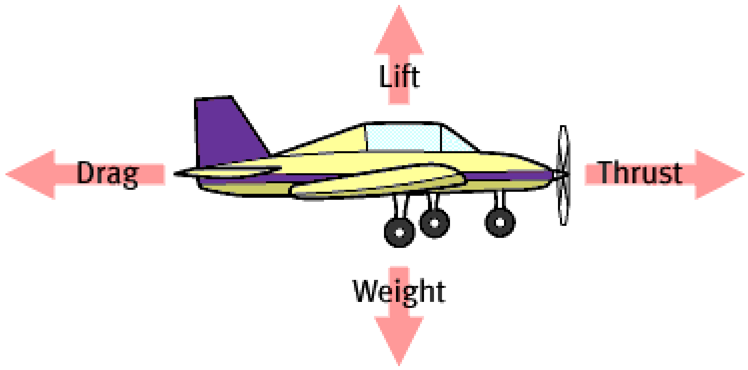
Instructions:

The following booklet contains information on How Airplanes Fly. Each page has a diagram as well as a few sentences. Please read the text and carefully analyze each picture. Try to understand the text and picture before proceeding to the next page of the booklet.

If you wish you can write in this booklet.

At the bottom of each page, there is a box with a rating scale. Please circle the number that corresponds to how easy or difficult it was for you to understand the concepts on the page: 1 (extremely easy) to 7 (extremely difficult).

Forces on an Airplane



While a plane is flying, there are four forces acting on the airplane. The forces are lift (upwards), weight (downwards), thrust (forwards), and drag (backwards).

How easy or difficult did you find the concepts on this page?

Extremely Easy			Moderate			Extremely Difficult
1	2	3	4	5	6	7

--- Page Break ---------------------------------------

Lift:

Lift is the force that causes an airplane to rise. The wings of a plane give it lift. Lift is caused by air movement and air pressure.

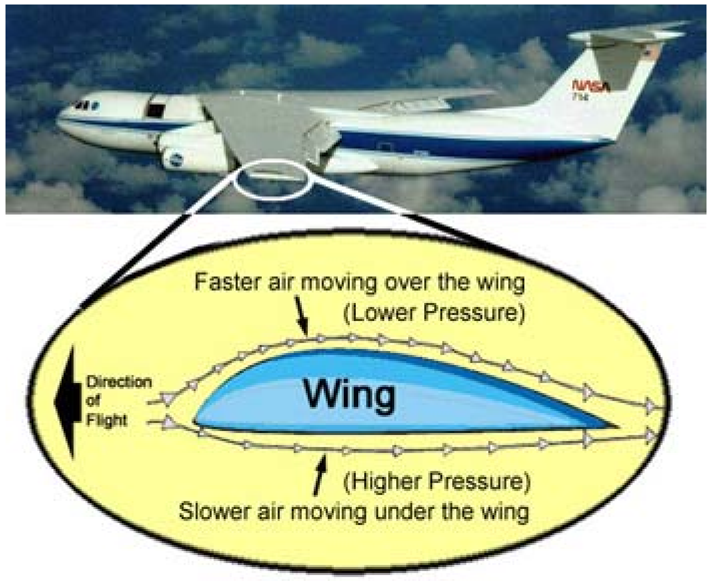
Let's learn more about **Bernoulli's Principle**, which explains how air pressure produces lift: Here's how it works. We live at the bottom of an ocean -- an ocean of air. This air presses on everything, and we call that AIR PRESSURE. Bernoulli discovered that air doesn't press as hard when it's moving. The faster it moves, the less it presses.

How easy or difficult did you find the concepts on this page?

Extremely			Moderate			Extremely

Easy						Difficult
1	2	3	4	5	6	7

The cross-section of a wing has curved top and flat bottom – this shape is called **airfoil.**



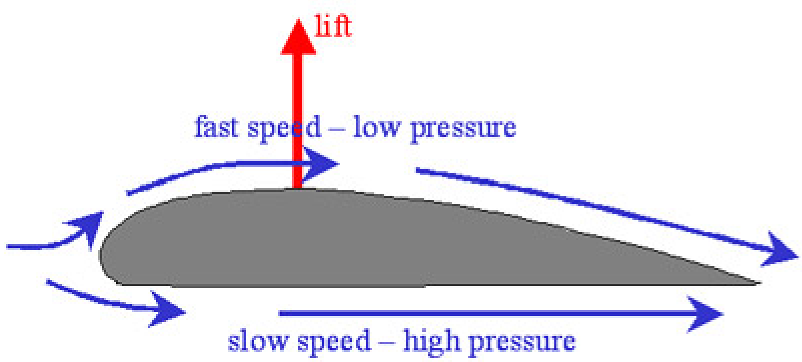
As airplanes fly, air is pushed above and below their wings. The air passing over the wing reaches the back of the wing at the same time as the air passing under the wing.

The air moving over the wing - which has further to travel around the curved surface - has to go faster than the air moving underneath.

How easy or difficult did you find the concepts on this page?

Extremely Easy			Moderate			Extremely Difficult
1	2	3	4	5	6	7

Air that moves slowly (the air going under the wing) creates MORE pressure than air that moves quickly (the air going over the wing). That means the air pressure pushing up on the bottom of the wing is greater than the air pressure pushing down on the top of the wing. Some people call the suction-effect on top of the wing. So the wing goes up. This is lift.



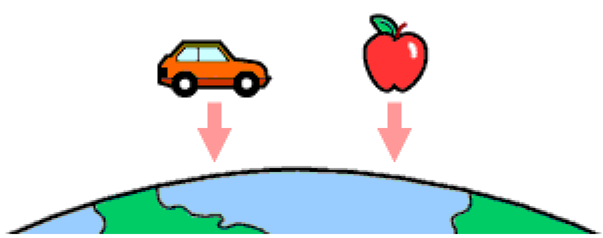
How easy or difficult did you find the concepts on this page?

Extremely Easy			Moderate			Extremely Difficult
1	2	3	4	5	6	7

-- Page Break ---------------------------------------

Weight:

All things have **weight**. That means how heavy or light an object is. Our bodies have a certain weight. The earth's gravity pulls down on objects, which gives them weight.



The gravity of earth pulls down on any object, even a flying plane. This is the plane's weight.

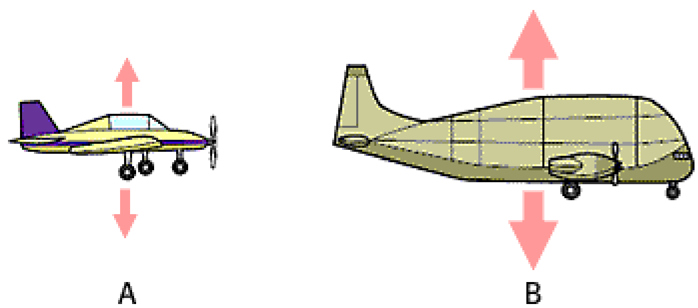
How easy or difficult did you find the concepts on this page?

Extremely			Moderate			Extremely

Easy						Difficult
1	2	3	4	5	6	7

The force created by lift needs to be greater than the weight of the plane in order for the airplane to take off.

A heavier plane needs more lift than a lighter plane in order to take off. So the weight of a plane determines how much lift is needed for the plane to fly. More weight, more lift!



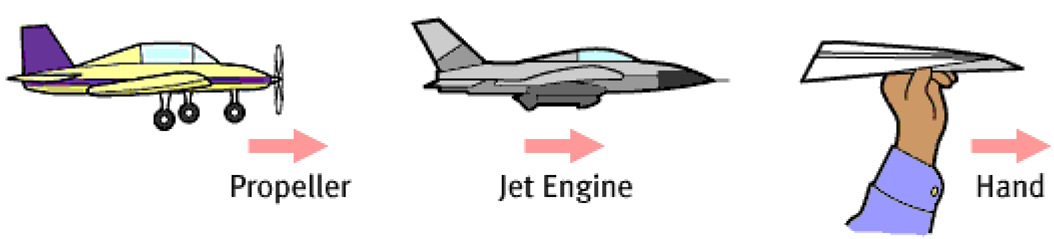
How easy or difficult did you find the concepts on this page?

Extremely Easy			Moderate			Extremely Difficult
1	2	3	4	5	6	7

-- Page Break ------------------------------- ---------

Thrust:

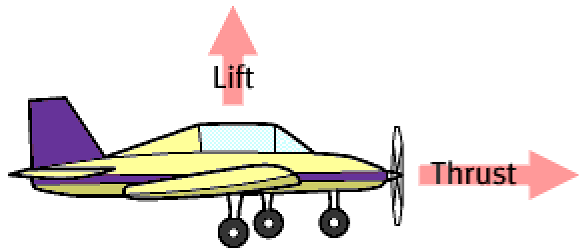
Thrust is the force that moves a plane forward. Engines usually provide thrust for airplanes, and the engine could be a propeller engine or a jet engine. Your hand provides thrust when launching a paper airplane.



How easy or difficult did you find the concepts on this page?

Extremely Easy			Moderate			Extremely Difficult
1	2	3	4	5	6	7

By moving the plane through the air, the engine's thrust keeps the plane flying. As long as air is flowing over the wings, lift is created, keeping the plane in the air.



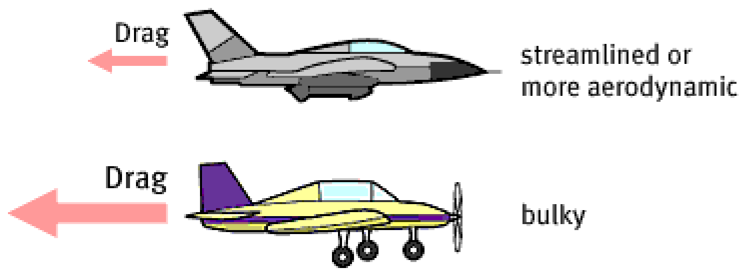
Both a jet engine and propeller give a plane thrust. The wings on a plane create lift, not thrust.

How easy or difficult did you find the concepts on this page?

Extremely Easy			Moderate			Extremely Difficult
1	2	3	4	5	6	7

Drag:

Drag is caused by the resistance of the wind or air against the plane. The shape and speed of an airplane determines how much drag it has. Drag can slow a plane down.



If two planes are flying at the same speed, the streamlined shaped plane will have less drag than the bulky shaped plane.

A plane is **aerodynamic** if it has little drag or bulk. A streamlined plane moves through the air more easily because its surface is smoother so the air flows easily over its surface. As a plane flies faster, drag will increase. That's why faster planes have to be more streamlined.

How easy or difficult did you find the concepts on this page?

Extremely Easy			Moderate			Extremely Difficult
1	2	3	4	5	6	7

When thrust is greater than drag, the plane speeds up.

When thrust and drag are equal the speed stays the same.

When drag is greater than thrust, the plane slows down.

Remember, speed increases when thrust increases, so if you increase your thrust, you will increase your drag a little bit as well.

How easy or difficult did you find the concepts on this page?

Extremely Easy			Moderate			Extremely Difficult
1	2	3	4	5	6	7

Note: *The Learning text without diagrams was identical to the above text, however there were no diagrams present. The instructions were given on the front page as follows:*

> The following booklet contains information on How Airplanes Fly. Each page has an empty box as well as a few sentences. Please carefully read the text and in the box, sketch a diagram related to the text. Draw everything you understand from the text, however don't spend time on making your pictures beautiful - think of them as sketches of what you see in your mind. Make the pictures useful to you, helping you understand the text.
>
> At the bottom of each page, there is a box with a rating scale. Please circle the number that corresponds to how easy or difficult it was for you to understand the concepts on the page: 1 (extremely easy) to 7 (extremely difficult).

Appendix D - Posttest

1. Explain how airplanes fly. Be very specific. If you want, you can use diagrams and examples in your explanation.

2. Plane A is smaller and weighs less than plane B. How much lift will Plane B need to get off the ground?
   a) same as A
   b) more than A
   c) less than A

3. While it is flying at a constant altitude, the thrust, created by the engine of this plane suddenly decreases and is less than the amount of drag. What will this plane do in the sky?
   a) speed up
   b) stay the same
   c) slow down

4. Now the engine is revved, so that thrust increases and becomes greater than drag. What does the plane do now?

   a) speed up
   b) stay the same
   c) slow down

5. A fire fighting plane just released its load of water over the forest fire, thus decreasing its weight. If the pilot does nothing to the engine controls, what will happen to the plane? It will…
   a) drop down
   b) rise in the air
   c) slow down

6. A roof is lifted off a building during a severe windstorm. Why does this happen? Be specific. You can use diagrams and examples in your explanation.