Transfer: A Review for Biology and the Life Sciences

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ABSTRACT

Transfer of knowledge from one context to another is one of the paramount goals of education. Educators want their students to transfer what they are learning from one topic to the next, between courses, and into the "real world." However, it is also notoriously difficult to get students to successfully transfer concepts. This issue is of particular concern in biology and the life sciences, for which transfer of concepts between disciplines is especially critical to understanding. Students not only struggle to transfer concepts like energy from chemistry to biology but also struggle to transfer concepts like chromosome structures in cell division within biology courses. This paper reviews the current research and understanding of transfer from cognitive psychology. We discuss how learner abilities, taught material, and lesson characteristics affect transfer and provide best practices for biology and life sciences education.

INTRODUCTION

Students often struggle to remember and apply previously learned material. Whether it is material from the previous day, unit, or even from other courses, teachers often find themselves having to prompt or reteach material that students are expected to already know. In some cases, it may be because students simply did not learn the material the first time around or have forgotten it in the interim. However, students often simply do not realize that the concepts they learned before apply in the new context. In other words, they learned the material, but fail to recognize it in a new context. It is also possible that students recognize that previous material is relevant, but they struggle to apply it. Transfer, the ability to generalize knowledge across contexts, is notoriously difficult (Detterman, 1993; Barnett and Ceci, 2002; Wooldridge *et al.*, 2014).

Students' inability to transfer prior knowledge or experiences is problematic: Many classes and programs rely on students' understanding of foundational knowledge in order to expand on that knowledge and learn more about a subject area. Within the life sciences, students struggle to transfer related concepts within courses, like the concept of chromosome structure within cell biology as it relates to mitosis versus gene expression (Newman *et al.*, 2012). Furthermore, students struggle to recognize and transfer fundamental concepts across disciplines, like recognizing that the concept of energy in a chemistry class is relevant to discussions about energy in a biology class (Kohn *et al.*, 2018). The curriculum, whether it be the order concepts are taught in primary and secondary school or the order of courses and prerequisites in a higher education program of study, is built with the expectation and understanding that students will transfer what they have learned from relevant course work to aid in their understanding of the life sciences as a whole.

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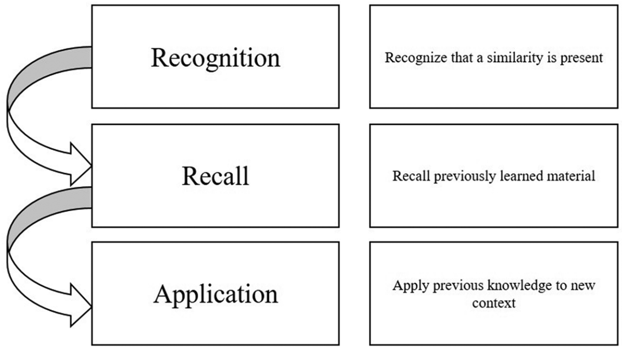

FIGURE 1. Steps in successful transfer.

Transfer is central to understanding material across the life sciences; however, it is often very difficult to achieve. This paper reviews the cognitive processes that underlie transfer in order to better understand why and when transfer does and does not occur in the hope that a better understanding of the processes that underlie transfer will help teachers improve transfer across the variety of disciplines that the life sciences encompass. We review research and theory on the cognitive processes needed for transfer, describe research and examples from biological science where these basic processes can be applied, and provide evidence-based suggestions for the classroom.

An Overview of Cognitive Processes in Transfer

Transfer is difficult, in part, because it is complex and comprises multiple steps (see Figure 1). To transfer a concept from one context to another, a student must first recognize that the previous knowledge is relevant, then recall that knowledge accurately, and finally apply the previous knowledge to the new context (Barnett and Ceci, 2002; Butler, 2010; Wooldridge *et al.*, 2014; Sumeracki *et al.*, 2019). Each of these stages—recognition, recall, and application—rely on several cognitive processes.

Students' ability to recognize that a previously learned concept applies in a new context depends on their *attentional processes* as well as their familiarity with, and *recognition* memory of, the concept. For example, energy is a central concept in physics, chemistry, and biology (see Kohn *et al.*, 2018). Students in a biology class, however, may fail to transfer their understanding of energy as discussed in the chemistry class, simply because they were struggling to pay attention during their biology class. Whether it was because a student had trouble dealing with distracting thoughts or blocking out irrelevant stimuli or was performing a particularly demanding task (Monsell, 2003; Engle and Kane, 2004; Vandierendonck *et al.*, 2010), failure to transfer a concept could be the result of attentional processes rather than a lack of understanding of energy. Similarly, the terms and the definitions used to discuss energy may be different between the two courses, resulting in students' failure to recognize that it is the same concept. They may have discussed "heat" or "potential" in one course, and failed to recognize the same concept when it is presented as "energy" or "work" in another course. Here a student fails to transfer because the previously learned concept was presented in unfamiliar terms.

Once students have recognized that previously learned information is relevant, they then have to *recall* that previously learned information. The ability to recall information depends on the relationship between the previously learned information (the *target*) and the concept they are currently trying to understand (the *cue*). Whether or not you remember something in response to a cue depends on factors like how frequently the cue and target are presented together, how long ago they were presented, and your practice at recalling the target in response to the cue (Anderson and Schooler, 1991; Karpicke and Roediger, 2007; Lehman *et al.*, 2014). For example, a student who has just attended lectures about the effects of pH and temperature on enzymes and enzyme kinetics can go into the associated laboratory that week and see the effects of those factors in a simple assay. When students are performing a lysozyme activity assay, they will mix the enzyme and the substrate together at varying temperatures or pH and then measure the level of substrate remaining over time. Performing this laboratory activity is a very different learning context than initially learning about the associated terms and processes in lecture. The likelihood that students will successfully transfer the concepts they learned in lectures about pH, temperature, enzymes, and enzyme kinetics will depend on how recent the lecture was and how much practice they had with those concepts before going into the lab.

Finally, once students have recognized a concept and recalled their understanding of that concept, they need to *apply* that understanding from the old context to the new context. This final stage relies on the students' schemas. Schema refers to one's knowledge about how information is related and categorized (Bartlett, 1932). We have schemas about what animals are likely to be kept as pets, what a scientist looks like, what we expect when we go to a restaurant, and so on. However, these all refer to knowledge structures that are shaped by our previous experiences. Students may recognize the term "energy" when they encounter it in their biology class, and they may even recall how they discussed energy in their chemistry class, but they struggle to apply that understanding to their biology class, because the two contexts are dissimilar. Their schema for what information is relevant in a biology class is different for what information is relevant in a chemistry class. Kohn *et al.* (2018) found that students felt energy was a central concept in their chemistry classes, but not their biology classes. They therefore tended to discount energy concepts in their biology classes.

A number of factors contribute to whether students will struggle with or succeed in transferring a concept. Some factors have to do with *learner abilities*—attention, previous experiences with the subject, and interest in the subject (Baddeley, 1986; Novick, 1988; Renninger and Hidi 2011). Others have to do with the nature of the *taught material* itself—how similar the current material is to the material they are expected to transfer or the presence of irrelevant, seductive details (Barnett and Ceci 2002; Rey, 2012). Finally, the *lesson characteristics* can affect whether students will be able to recognize when previously taught material is relevant. Being mindful of how examples are used, presenting complementary ideas and materials together, and holding student attention can all affect transfer (Kang, 2016; Weinstein *et al.*, 2018). In this paper, we draw on examples from biology and the life sciences to discuss how learner abilities, taught material, and lesson characteristics affect transfer.

LEARNER ABILITIES

Attention

A student's ability to recognize a previously learned concept in a new situation or context depends critically on whether that information was properly encoded. Therefore, the first step in the ability to transfer is also the first step in encoding and a critical process for retrieval; transfer depends on the learner's attention. There are, notably, clinical disorders that affect attentional processing, such as attention deficit hyperactivity disorder (ADHD) and attention deficit disorder (ADD). However, outside of ADHD and ADD, a wide range of attentional skills and abilities exists. Attentional control varies between people (Unsworth and Engle, 2007) and is strongly associated with academic performance (Gathercole and Pickering, 2000) and a student's ability to transfer (Cho *et al.*, 2007; Simms *et al.*, 2018).

Attentional control will determine whether a student can successfully block out irrelevant information or successfully switch between tasks while engaging in a multistage process. These two uses of attention are *selective* and *divided* attention, respectively. A student employing selective attention is able to focus on the information being presented or on the task at hand without being distracted (Treisman, 1964). Sometimes it is necessary to complete more than one task or to have other stimuli capture your attention, and you must therefore use divided attention (Monsell, 2003). This use of divided attention is necessary to complete everyday tasks, and is particularly relevant when completing laboratory exercises. However, it can lead to errors in learning and transfer because of the complex attentional dance that occurs when we divide our attention.

When our attention is divided, we rapidly switch between tasks in *serial* (Brown and Kaminske, 2018). This task-switching happens rapidly and at a cost. The cost may be minimal or quite severe depending on whether the tasks are easy or familiar to us, or if they are challenging or novel to us (see Vandierendonck *et al.*, 2010). Task-switching leads to more errors, slower response times, and decreased memory for the material (Monsell, 2003; Wammes and Fernandes, 2016). Task-switching makes it more difficult for students to engage in transfer, because it impairs their ability to recognize previously learned concepts. Many laboratory and classroom exercises require students to switch between multiple tasks. For example, teaching the process of polymerase chain reaction (PCR) and analysis in laboratory courses involves downtimes and multiple steps. Once a group of students has completed the steps to set up the PCR in the thermocycler, there is a variable amount of time until the reaction is completed. During this time, the students prepare for the analysis of the reaction by pouring an agarose gel on which the newly amplified PCR DNA fragment will be isolated. At the same time, everything related to the experiment and the results are recorded in a lab notebook to analyze post-experiment. A student's ability to transfer and apply concepts learned in lecture over to laboratory exercises might suffer due to divided attention during laboratory exercises. This, in turn, may reduce the student's ability to transfer concepts to the next course in the sequence.

Students vary in attentional control abilities (Unsworth and Engle, 2007), making it challenging for a teacher to accommodate all learners in the classroom. However, some best practices can improve selective and divided attention for all students. A simple way to address the needs of students with a poor ability to block out irrelevant stimuli (i.e., students who struggle with selective attention and get easily distracted during lessons) is to reduce visual distractions and noise in the classroom (Hanley *et al.*, 2017). Presenting advanced organizers or an overview of the lesson or laboratory activity can help mitigate the effects of divided attention (Brown and Kaminske, 2018). When students are given time to prepare to switch tasks, or if the tasks they are switching between are more familiar to them, it lessens the cost of task-switching (see Vandierendonck *et al.*, 2010). Similarly, teachers should consider ways to reduce off-task multimedia use (Loh *et al.*, 2016). Cell phones, laptops, and other multimedia devices provide many opportunities for unnecessary task-switching that divides student attention. These devices can also provide engaging, interactive, and generally enriching learning experiences as well. Therefore, teachers need to weigh the costs and the benefits of including these technologies in classroom activities.

Prior Knowledge and Expertise

Students' ability to transfer knowledge from one context to another depends on their level of prior knowledge on the subject (Novick, 1988). This is due, in part, to the fact that those with more prior knowledge are better at noticing when two situations are similar and transfer might be possible. However, the contexts will not always be similar, and students often need to transfer across a number of different situations. Having a greater knowledge base helps students notice that two situations are related, making transfer more likely to occur.

Experts, or those with extensive knowledge on a topic (Ericsson and Charness, 1994), tend to represent problems differently than novices, or those who are new or inexperienced. For example, Chi *et al.* (1981) demonstrated that experts and novices classified physics problems differently; they found that experts were more likely to classify problems using their underlying structure, or the major principles that determine how to approach the problem. Yet novices tended to focus on surface features of a problem that may be irrelevant to how the problem ought to be solved. Similarly, Southard *et al.* (2016) investigated how students organized their knowledge around core concepts in molecular and cellular biology—DNA replication, transcription, and translation. They found that students were able to classify these molecular mechanisms, but novices tended to conflate these categories, while more advanced students did not. Importantly, transferring from one situation to another typically involves transferring some underlying structure or major principle (Gick and Holyoak, 1983). Because transfer revolves around a student's ability to notice the shared processes or underlying principles between two situations (Kattner *et al.*, 2017), when students represent problems based on the underlying principle, they are more likely to notice a transfer situation. When students focus on surface features, it makes it more difficult for them to transfer.

For example, students may learn about how acidity is involved in human digestion, and later about ocean acidification (Davidesco and Milne, 2019). Students with greater background knowledge may be more likely to see the connection between how acidity affects both human digestion and ocean life. If the students understand the underlying principles from both lessons, then they will be more likely to transfer knowledge from one situation to the other. However, if students focus instead on the surface details, such as the fact that the lesson involves information about food breaking down or animals that live in the ocean, then they will be less likely to notice the similarities that afford the opportunity to transfer.

As teachers, it is important to keep in mind that students are often novices in the topic area. This is especially true in courses that occur earlier in a student's education (e.g., earlier grades in school, introductory courses, science courses for nonmajors). Thus, instructors should be aware that students may not readily see the underlying structure of the information presented, making transfer more difficult. These students in particular will need additional practice with many different types of problems to make it easier for students to increase background knowledge and learn how to represent problems in a way that focuses on structural features (Hogan and Rabinowitz, 2009). Further, additional practice transferring from one context to another will make it more likely that students will notice opportunities for transfer in the future, and while it would be impossible to give students practice transferring in every situation that might arise, more practice will certainly make transfer more likely. In particular, giving students practice transferring when the surface details of the problems are different will help students to work past the surface features and use the underlying structure of the problem. This will be discussed more in the *Lesson Characteristics* section.

Finally, while students are often novices in the topic area, teachers are experts. As experts, teachers are more likely to naturally view and categorize problems based on underlying structure, and thus naturally see connections between related problems. Because connections may seem very obvious to teachers, it might be difficult for teachers to recognize when students will struggle to see connections (sometimes referred to as "the curse of knowledge"; Camerer *et al.*, 1989). Teachers can help their students by remembering that these connections are not as obvious to the students, and novice students will need more direct instruction or scaffolding while they learn to make connections based on underlying structure.

Interest

A common approach for improving transfer and learning in the classroom is to appeal to students' interests in order to motivate students to engage with the material. Interest itself, however, is not a single cognitive or psychological process (Renninger and Hidi, 2011), making it difficult to assess whether interest improves transfer. Instead, interest can be *situational*, dependent on how the instructor shapes a lesson and a student's attention, or *individual*, dependent on the student's prior knowledge and expertise (Hidi and Renninger, 2006).

Situational interest refers to a student's focused attention and engagement with a particular concept (Renninger and Hidi, 2011). Classroom demonstrations, hands-on activities, and timely or relevant references to current events may all be ways in which an instructor tries to capture students' situational interest and encourage them to transfer or apply what they have been learning in the course. For example, a video of bacteria mutating and surviving in increasingly intense concentrations of antibiotic can provide a striking demonstration of how certain pathogenic bacteria have become resistant to most currently available antibiotics, and thus display the importance of limiting the use of antibiotics to only those situations where it is warranted. However, a student who is distracted or has poor attentional focus may not transfer the concept of bacteria mutating from the video to the larger concept of restricting antibiotic use. Therefore, teachers should be mindful of the range of individual differences in attentional focus (Unsworth and Engle, 2007) when evaluating the effectiveness of their in-class demonstrations.

Situational interest has been found to have mixed effects on learning and transfer (Pugh and Bergin, 2006). Situational interest has been found to predict recall and reading comprehension (Krapp, 1999; Hidi, 2001) but also to distract from the learning goals of an activity (Bergin, 1999). While situational interest, that is, the kind of interest garnered by in-class demonstrations and hands-on activities, might not directly influence learning and transfer, it sets the groundwork for the next stage of interest: individual interest.

Individual interest refers to a student's sustained engagement with and developed knowledge of a particular concept (Hidi and Renninger, 2006). Students with an individual interest in a topic have better prior knowledge of that interest area (Alexander *et al.*, 2008) and therefore will be likely to transfer their knowledge about that topic (Novick, 1988). A classic example of individual interest, particularly in young learners, is a childhood obsession with dinosaurs (Chi and Koeske, 1983; Chi *et al.*, 1989). Despite little formal training on the topic, children with a particular obsession for dinosaurs can develop an incredibly rich taxonomical understanding of dinosaurs (Chi and Koeske, 1983). Similar levels of organized knowledge have also been found in children with strong interests in birds (Mervis *et al.*, 2003).

Students with a well-developed individual interest in a topic become, to a certain extent, experts on that topic. As experts they are more likely to organize their knowledge about the topic differently (Ericsson and Charness, 1994), which helps them to notice the shared processes or underlying principles between two situations and thus improves their ability to transfer information across contexts (Kattner *et al.*, 2017).

While interest is certainly an asset in learning a topic, teachers should be aware that not all forms of interest are equal. Students who have a well-developed interest may also have the background knowledge and motivation that will help them notice similarities and persist longer when transferring concepts from one class to another. Students whose interest was triggered situationally, or who have had less time and experience to develop their interest, will struggle to make connections and transfer understanding across contexts.

By providing students with opportunities to re-engage in personally meaningful ways with material, teachers can help students transform situational interest into individual interest, while also improving individual interest for those who are already invested in the topic. Project-based learning, one-on-one tutoring, and cooperative group work can encourage individual interest (Mitchell, 1993; Schraw and Dennison, 1994; Hoffmann, 2002; Hidi and Renninger, 2006). Project-based learning in particular is a popular approach within biology and the life sciences, generally exhibiting improvements in learning and transfer gains compared with non–project based approaches (see Beach and Alvarez, 2015; Berchiolii *et al.*, 2017; Costa-Silva *et al.*, 2018). For example, a project-based learning approach in

Near ⟵⟶ Far

Knowledge domain	Mouse vs. rat	Biology vs. botany	Biology vs. economics	Science vs. history	Science vs. art
Physical context	Same room at school	Different room at school	School vs. research lab	School vs. home	School vs. beach
Temporal context	Same session	Next day	Weeks later	Months later	Years later
Functional context	Both clearly academic	Both academic but one non-evaluative	Academic vs. filling in tax forms	Academic vs. informal questionnaire	Academic vs. at play
Social context	Both individual	Individual vs. pair	Individual vs. small group	Individual vs. large group	Individual vs. society
Modality	Both written, same format	Both written, multiple choice vs. essay	Book learning vs. oral exam	Lecture vs. wine tasting	Lecture vs. wood carving

FIGURE 2. A taxonomy of transfer adapted from Barnett and Ceci (2002).

cell biology improved dental students' ability to recognize the relevance of cell biology to dentistry and improved their ability to produce reports that focused on scientific methodology and its relationship to dentistry (Costa-Silva *et al.*, 2018).

TAUGHT MATERIAL

Near versus Far Transfer

The ability to transfer also depends on the similarity of the learned material and the transfer situation. In a landmark paper, Barnett and Ceci (2002) developed a taxonomy for transfer, explaining that the probability of successful transfer depends on how closely the transfer context matches the learning context across several domains. When the learning and transfer situations are very similar, this is called *near transfer*, and when they differ substantially, this is called *far transfer*. Near and far transfer exist on a continuum, such that any given situation is not categorically near or far, but may be described relative to other situations. For example, applying information about plant biochemistry to biodiversity is relatively near transfer, whereas the application of plant biochemistry to climate change policy involves far transfer by comparison.

Barnett and Ceci (2002) described several different dimensions across which transfer could occur (see Figure 2). Information can be transferred across different *knowledge domains* (as in the example just given) or across *physical contexts*, such as studying in a library and applying in a classroom. Information is also transferred across *temporal contexts*, as when students apply the information they have learned months later when they take the next course in a sequence. Barnett and Ceci also talk about the *functional context*—is the information clearly academic or is the transfer from the academic world to the "real" world, as when applying information from the classroom to make decisions at the grocery store? Transfer can also take place in different *social contexts*—applied from one person to society—or across different *modalities*—heard in a lecture versus answering multiple-choice questions.

Any given transfer situation involves all of these domains and the likelihood of successful transfer depends on how near or far the transfer situation is in each domain. Consider a student who learns about basic principles of genetics in an introductory biology course and over winter break has a conversation with a family member about the probability that his or her child will be born with brown eyes. This is fairly near transfer in the knowledge domain, as the two pieces of knowledge are closely aligned. The physical context is quite different (farther transfer), from the classroom to the student's family gathering, but the temporal context is relatively near, as the student learned this concept just this semester. The functional context has changed from course work to discussing the expectant child, but the social context still involves knowledge acquired individually being transmitted individually (near transfer). Finally, the modality is likely quite different (far transfer), from reading and answering exam questions to having a conversation. Taken together, we can see the various barriers that the student might experience in trying to apply information learned in class to this new context.

The framework developed by Barnett and Ceci (2002) has been used to explain successful and unsuccessful transfer in a number of retrieval practice experiments. Retrieval practice refers to the phenomenon that bringing information to mind (often via a quiz or test) strengthens the memory for that information (for review, see Roediger and Butler, 2011). Butler (2010) examined whether retrieval practice could help students transfer their knowledge about bat wings to a new design for airplanes and found evidence of successful transfer. Wooldridge *et al.* (2014) also attempted to use retrieval practice to help students transfer but were unsuccessful. The primary difference between the two studies lies in the degree of transfer. Whereas Butler asked students to transfer from bat wings to airplane wings (relatively near transfer in the knowledge domain), Wooldridge and colleagues asked students to transfer from one concept in a section of a book chapter on evolution to another concept from that same section. For example, one quiz question asked about the "molecular clock" and the fossil record and another question from the same section asked about the relationship between evolution and genetic differences across species. While these two concepts came from the same section of the textbook chapter and are topically related, the transfer between the two concepts is much farther in the knowledge domain.

The similarity between materials is not always readily apparent. However, to optimize transfer, it is best to anticipate the transfer situation and design materials that will increase the likelihood of success. For example, in a study investigating transfer between biology and physical education (PE) classes (Spintzyk *et al.*, 2016), students were either taught biology and PE lessons in interdisciplinary combined blocks or as separate classes addressing the same topics. All students were taught about concepts that were relevant to human biology in both PE and biology—that is, muscle contraction, the cardiovascular system, nutrition, and so on. The students in the interdisciplinary lessons were taught by first providing the biological background, then leading students through a practical demonstration in PE exercises, and finally, allowing a chance for students to observe and reflect on the relationship between the two. Students in the comparison group covered the same material in their biology and PE classes, but without any direct references to the other class and without blocking the classes together. Students in the interdisciplinary class performed significantly better than the control class on tests of recalling and applying their knowledge (Spintzyk *et al.*, 2016). Furthermore, follow-up interviews found the interdisciplinary group to be more interested and motivated to engage with the topic (in this case, endurance training). This interdisciplinary approach required teachers to coordinate and design materials that would be appropriate for facilitating transfer. By teaching both content areas jointly, they reduced the distance between the two contexts (biology and PE) in their physical, temporal, and functional contexts.

Seductive Details

One way to increase student interest in and attention to a topic, and thus help them learn and transfer the information, could be achieved through adding entertaining, but irrelevant, information (funny anecdotes, interesting images or statements, etc.) alongside the main concepts that are being taught. Information that is irrelevant for the understanding of the main concept, but is in itself interesting, has been coined "seductive details" (Garner *et al.*, 1989). Seductive details, by and large, have detrimental effects on learning outcomes and transfer (Rey, 2012). However, there are boundary conditions that can eliminate the detrimental effects of seductive details (Eitel and Kühl, 2019).

Adding seductive details can make it difficult for learners to successfully transfer between tasks and contexts for three reasons (Harp and Mayer, 1998): First, seductive details can distract the learner's attention away from the important information toward the more entertaining information—at the expense of engaging with the important information. Second, the presence of seductive details can interfere with making connections between different important ideas in the material that lead to deeper understanding. Finally, irrelevant details can activate misleading schemas in memory that can hinder understanding of the material altogether. Activating wrong prior knowledge can harm comprehension, and in turn, make transfer impossible. Thus, seductive details can hinder the essential processes that are necessary for successful transfer. Furthermore, adding irrelevant pieces of information during instruction unnecessarily increases attentional demands in the learner. Attention is the first step to distinguish important details from unimportant ones, to organize the material that is being learned, and to activate correct prior knowledge and integrate new knowledge into existing schemas. Thus, presenting learner with irrelevant details can decrease their processing of relevant information—as a result, transfer performance decreases.

In a series of experiments, Harp and Mayer (1998) presented participants with two types of instructional booklets on lightning: In one condition, the booklet only included relevant details and graphs to explain the phenomenon. In the seductive details condition, the booklet included irrelevant statements ("Golfers are prime targets of lightning strikes") and irrelevant images alongside the main, relevant text. Participants showed lower transfer performance in the seductive details condition compared with the no seductive details condition—neither signaling relevant details (via highlighting to draw their attention) nor providing learning objectives (to better guide their studying of the material) decreased the negative effects of seductive details on transfer (for a similar finding, see Abercrombie *et al.*, 2019). Other studies came to the same conclusion: Seductive details—through the mechanisms described earlier—hinder learning and decrease students' transfer performance (e.g., Garner *et al.*, 1991; Lehman *et al.*, 2007). In addition, the detrimental effects of seductive details increase as interest in the details increases (Mayer *et al.*, 2008).

While the majority of research on seductive details has investigated its effect on learning from text, negative effects on transfer also occur with seductive pictures (e.g., Wiley, 2019) and while attending lectures or watching instructional videos (e.g., Harp and Maslich 2005; Mayer *et al.*, 2001). Magner *et al.* (2014) investigated the effect of decorative visuals on near- and far-transfer performance for students studying geometry with varying prior knowledge. They found that adding decorative images had a detrimental effect on near-transfer performance. More strikingly, they revealed that students with low prior knowledge were hindered more by these illustrations than students with higher prior knowledge. In fact, only students on the highest end of prior knowledge for the topic benefited from decorative illustrations.

Even when no negative effects of seductive details on performance occur, people take longer to process relevant information when seductive details are present, simply because they are distracted (Strobel *et al.*, 2019). Gardner *et al.* (2016) investigated practical transfer of laparoscopic surgical skills in undergraduate medical students after watching instructional videos including or excluding seductive details. Students performed better on the transfer of the suturing task when seductive details were absent. Plus, the students reported higher attentional demands when seductive details were included, and this mediated the seductive details effect, leading to lower transfer performance.

Although the overwhelming evidence suggests avoiding seductive details in instruction, using seductive details can trigger situational interest in the learner, which can be beneficial from a motivational standpoint (e.g., Wang and Adesope, 2016). Research has revealed important boundary conditions that eliminate negative effects. Clearly pointing out to students that the seductive details are irrelevant for the understanding of the main concepts (Eitel *et al.*, 2019; McCrudden, 2019) or enriching instruction with student-led activities, such as note-taking (Wang *et al.*, 2017) or writing summaries (Jaeger *et al.*, 2018) can help. Beside these instruction-focused interventions, prior knowledge is an important learner-focused factor moderating the seductive details effect (e.g., Magner *et al.*, 2014). For example, note-taking improved transfer performance with material that included seductive details for students with low prior knowledge, but students with high prior knowledge were not affected by the note-taking instruction—they performed well either way (Wang *et al.*, 2017). Interestingly, the negative effects of seductive details seem to disappear when students are in high-stakes learning environments (Fries *et al.*, 2019). This is good news for educational settings, which usually are high stakes by nature. Fries *et al.* (2019) found that students with high prior knowledge were not affected by seductive details independent of whether the learning context was low or high stakes, but students with low prior knowledge showed the best performance in a high-stakes learning environment when seductive details were present.

While a large number of empirical studies suggest removing seductive details in instruction because of their negative impact on transfer, careful consideration of boundary conditions, for example, being specific about the irrelevance of the seductive detail and introducing student-led learning activities such as note-taking, can help paint a more nuanced picture that allows for the inclusion of interesting details to engage the learner.

LESSON CHARACTERISTICS

Multiple Examples

Spontaneous transfer can be very difficult to achieve; however, one way to help students see connections and encourage transfer is to provide multiple examples of the concept. Examples help students to activate prior knowledge (Reed and Evans, 1987). Examples are often more concrete than the abstract representation of a concept, and concrete information is remembered better than abstract information (see Weinstein *et al.*, 2018). Further, when students have more examples, it makes it easier for the students to see how a concept or idea is applied in various situations.

The vast majority of teachers are likely already using concrete examples in their teaching (Weinstein *et al.*, 2018). However, what seems to be important for transfer is using multiple examples of the same concept that involve different surface features (Gick and Holyoak, 1983; but see also Kaminski *et al.*, 2008). In a series of experiments, Gick and Holyoak (1983) showed that providing students with the underlying principle, asking students to summarize the underlying principle, and even providing a diagram did not help improve transfer from one problem to another, but providing multiple examples with different surface features did help. Providing examples containing different surface features with the same underlying principle makes it easier for students to see how the underlying structure is applied in different contexts. Even still, students benefit from direct instruction about how the examples are all related to one another and the underlying principles connecting them (Berry, 1983), especially when they have lower levels of background knowledge on the topics (see the *Learner Abilities* section).

Teachers can improve the likelihood of transfer by providing multiple examples that demonstrate the key concepts within a lesson, taking care to create examples that have different surface features and pointing out the similarities across the examples to students. For example, the protein structure–function relationship is a fundamental concept in cell biology that is reinforced in understanding a variety of processes in the cell; including how signal transduction pathways occur in cell signaling, how enzymes are regulated in metabolism, and how transcription factors bind DNA in gene expression. If only one example is provided, the students may focus more on the surface features of the example than the underlying principle being applied, especially as novices (Chi *et al.*, 1981).

Further, as mentioned earlier, teachers can encourage transfer by doing their best to anticipate the most likely ways students might use the information in the future and providing examples in those areas. Not only does this create transfer that is relatively near, but diverse examples that contain different surface features will make it more likely that students will notice that transfer is possible in future situations.

Interleaving

When students have a deeper understanding of the underlying principles of an idea, they will be more likely to notice connections between that idea and a concept presented in a new context, paving the way for transfer. Interleaved practice is one way to achieve this. Interleaving introduces variability during practice by mixing up related topics and practicing them together instead of in blocks of homogenous topics (termed *blocked practice*) and has been shown to increase learning and transfer performance on a final assessment (Kang, 2016). To give a simple example, mathematics teachers can create worksheets that jumble up multiplication, division, addition, and subtraction exercises instead of worksheets that block each of those procedures into similar sets (e.g., five exercises on addition then five on subtraction and so on). Similarly, when teaching gene expression, teachers can create exercises that jumble up examples of replication, transcription, and translation in order to help students differentiate between those processes.

Three mechanisms contribute to the benefits of interleaved practice: discriminative contrast, retrieval, and spaced practice. *Discriminative contrast* is an important process triggered by interleaving related topics or problem types. When students interleave related types of tasks and work on them back-to-back or side-by-side, they are more likely to notice ways in which the tasks are similar to and different from each other. This discriminative contrasting allows students to obtain a deeper understanding of the material (Birnbaum *et al.*, 2013). *Retrieval* from memory is required when students work on juxtaposed tasks that differ in what procedure they need to apply in order to complete those tasks. Thus, interleaving ensures that the learner retrieves adequate procedures, selects the correct one, and applies it for each item. For blocked practice, however, the learner simply needs to apply the previously used procedure to all problems within a block—without further reflecting on each item and retrieving the procedure from memory. *Spaced practice* (Cepeda *et al.* 2006) further contributes to the benefits of interleaving (Foster *et al.* 2019), because interleaving naturally introduces spacing between solving one type of problem and solving it again after other problem types have been worked on. Taken together, the mechanisms promoted by interleaved practice allow students to obtain a better understanding of the underlying principles of the material, which equips them to recall, select, and apply the correct procedures to tasks in novel contexts.

Interleaved practice has been shown to be beneficial for a variety of science, technology, engineering, and mathematics (STEM) skills, such as science category learning (e.g., Eglington and Kang, 2017), mathematics learning and problem solving (e.g., Mayfield and Chase, 2002; Goldin *et al.*, 2014; Rohrer *et al.*, 2015), and complex skill acquisition (e.g., Vakil and Heled, 2016). In the study by Eglington and Kang (2017), students practiced how to categorize organic chemical compounds into the correct chemical categories either using blocked or interleaved practice. On a delayed test 2 days later, students in the interleaved practice condition outperformed students who had practiced in a blocked manner on categorizing novel exemplars. Rohrer *et al.* (2019) tested the effects of interleaved practice in mathematics learning in 54 middle-school classrooms over the course of approximately 5 months. The experiment was completely embedded into the usual classroom routine and implemented by the teachers. Interleaved practice was implemented via eight worksheets. Math problems (solve inequality, interpret graphs, geometry, and simplify expressions) on the worksheets were either presented in a blocked or an interleaved manner. A month after the end of practice, students took a surprise test on new problems of the types practiced before: Students in the interleaved condition performed better (61%) than students in the blocked condition (38%). Although this experiment did not investigate transfer per se, it highlights the potential of this strategy for application in real STEM classrooms, because it can be easily implemented by teachers without consuming too much of their time. Benefits of interleaving have been shown for younger students as well. Nemeth *et al.* (2019) revealed that interleaving math tasks on the application of different types of shortcuts and decomposition strategies in subtraction led elementary students to apply their acquired skills more flexibly and to correctly select the appropriate procedure to solve new problems.

There are two important aspects that should be taken into consideration when implementing interleaving in practice. First, to provide students with a chance to engage in discriminative contrast when interleaving different examples or problem types, it is crucial that they have obtained an initial understanding of the task. For that reason, interleaving works best after a period of blocked practice—and this is particularly true when students have low prior knowledge of the concepts in the beginning (Rau *et al.*, 2010). Second, interleaving usually leads to lower performance *during* practice than blocked practice. However, the additional effort during interleaved practice pays off in the long-term, when interleaving shows less material is forgotten than with blocked practice (Taylor and Rohrer, 2010).

SUMMARY

Whether or not a student can generalize knowledge from one context to another depends on a multitude of cognitive processes. Transfer itself is a multistage process wherein the student must first recognize that there is a similarity between the material, recall what has been previously learned, and correctly apply that knowledge to the new context. Learner abilities, taught material, and lesson characteristics can affect each of those stages in different ways.

Given the complexity of transfer, it is not surprising that is often difficult to achieve (Detterman, 1993; Barnett and Ceci, 2002; Wooldridge *et al.*, 2014). However, there are some practical recommendations that follow from the research.

Attention

While teachers cannot control whether students come into their classrooms with better or worse attentional abilities, there are a number of ways that teachers can modify their lessons or their classrooms to improve focus. Reducing the number of visual distractions in the classroom (Hanley *et al.*, 2017), providing advance organizers (Brown and Kaminske, 2018), reducing off-task multimedia use (Loh *et al.*, 2016), designing classroom and lab activities that minimize task-switching, and providing explicit and direct instruction on what students are expected to transfer can help students focus attention in class, thus making it more likely that they will be able to remember the information to transfer later.

Prior Knowledge and Expertise

Typically, students come into the classroom as novices with very little prior knowledge. Their impoverished knowledge base makes it difficult to notice when two situations are related, making transfer less likely to occur. Teachers, on the other hand, have a much richer knowledge base, making connections appear very obvious. This makes it difficult for teachers to recognize when students will struggle to see connections. Providing direct instruction and scaffolded practice (Berry, 1983) can help students make connections between related material.

Interest

Students who have a well-developed individual interest have a well-developed knowledge base (Chi and Koeske, 1983) and an increased motivation to transfer their knowledge to new situations (Alexander and Murphy, 1998). On the other hand, students whose interest was only triggered situationally, or who have had less time to develop their interest, do not have the benefit of a well-developed knowledge base or the motivation to persist to help them transfer. Teachers can foster individual interest by providing students with opportunities to re-engage with the material in personally meaningful ways (Mitchell, 1993; Schraw and Dennison, 1994; Hoffmann, 2002; Hidi and Renninger, 2006).

Near versus Far Transfer

The similarity between material can vary along several dimensions: knowledge domains, physical contexts, temporal contexts, functional contexts, social contexts, and modalities (Barnett and Ceci, 2002). The extent to which material is near or far in any given domain can affect a student's ability to transfer. It is not always possible to predict how students will need to remember and apply a piece of information in the future or when they will need to do so. However, to the extent that teachers can anticipate future transfer situations, course materials can be designed to be similar to those situations in order to increase the likelihood of transfer.

Seductive Details

Seductive details are entertaining, but irrelevant, information that is presented alongside relevant course material. While these details can often make the material more interesting, they often do so at the cost of successful memory and transfer (Harp and Mayer, 1998). The simple recommendation is to avoid using seductive details in instruction. However, clearly informing and pointing out that seductive details are irrelevant or engaging students in note-taking can reduce the negative impact of seductive details (e.g., Eitel *et al.*, 2019; Wang *et al.*, 2017). Prior knowledge also plays an important role in deciding whether to include seductive details or not—while students with low prior knowledge have a hard time coping with the additional attentional demands imposed by seductive details, students with high prior knowledge are less affected (e.g., Magner *et al.*, 2014).

Multiple Examples

Providing multiple examples of concepts helps students activate prior knowledge (Reed and Evans, 1987) and, often, provides more concrete representations of a concept or idea (Weinstein *et al.*, 2018)—both factors that improve transfer. When providing multiple examples, teachers should take care to use examples that have different surface features (Gick and Holyoak, 1983) and that are similar to possible future transfer situations (Barnett and Ceci, 2002) and to provide direct instruction on similarities across the examples (Berry, 1983).

Interleaving

Introducing variability during learning by mixing up related topics and practicing them together improves students' understanding of underlying principles and connections, which in turn improves transfer. When presenting material in an interleaved manner, teachers should be aware that performance is low, initially. However, this low initial performance is the result of the additional effort of discriminating between related topics and leads to better long-term performance (Taylor and Rohrer, 2010). Furthermore, it seems important to make sure that students exhibit a good grasp of the different concepts before introducing interleaving. A short period of blocked practice preceding interleaved practice seems to be optimal.

DIRECTIONS FOR FUTURE RESEARCH

The majority of research reviewed in this paper comes from cognitive and educational psychology. Research in psychology relies heavily on the experimental method by setting up different conditions (usually including a control condition) and randomly assigning participants to these—allowing causal inferences to be drawn. We have reviewed a mix of laboratory and classroom experiments with authentic material studied in the educational settings to add to the breadth of the review. However, research on transfer in STEM would massively benefit from a collaborative multimethod approach. For example, it could be insightful to start with observational studies looking at different strategies to enhance transfer first (e.g., Kryjevskaia *et al.*, 2013; Yeong, 2015) and, based on these, design experiments in the laboratory and field to further test these ideas to draw causal conclusions. Thus, future research should work on collaborative projects between science education and cognitive psychology research to broaden the scope of the practical recommendations.

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