The Potential of Embodied Cognition to Improve STEAM Instructional Dynamic Visualizations

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Abstract An embodied cognition perspective recognizes that the evolution of the human mind has been shaped by the evolution of the species' whole body in its interaction with the environment. For example, hand actions—such as object manipulations and gestures—have been fundamental for human survival, and thus they continue to trigger different areas of the evolved mind. One of these areas is the mirror neuron system, a major processor of bodily movement, which allows humans to learn manipulations and gestures with relative ease. A clear implication for instruction, across many Science, Technology, Engineering, Arts and Mathematics (STEAM) topics, is to profit from the effortlessness of hand actions in order to enhance the learning of difficult concepts or challenging educational materials. One example of demanding instructional materials is dynamic visualizations (e.g., animation, video), which can be too transient to follow, understand and learn from. However, we argue that dynamic visualizations may overcome the transiency problem by including embodied activity. In this chapter, we will review a diverse number of studies that show the instructional benefits of embodied cognition, manipulations, and gestures. Specifically, we will address how these evolved skills can be employed to effectively learn from STEAM dynamic visualizations.

Keywords Embodied cognition · Biologically primary ability · Manipulation · Gesture · Static versus dynamic visualization · Spatial ability

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Dynamic Visualizations and Instruction

A visualization can show static or moving elements. In the latter case, it is referred to as a *dynamic picture* or *dynamic visualization*, where *animation* and *video* are the most popular examples, intersecting with many facets of a modern student's life. To mention one example of the popularity of these dynamic visualizations, Tang and Austin (2009) observed that, among five instructional methods (video, PowerPoint, projector, Internet, and lecture), the strongest association reported by students with the variable *enjoyment* was with video. Given this outcome, this enjoyment of animation and video should be aligned with the educational potential of dynamic visualizations.

Learning Opportunities Fostered by Dynamic Visualizations

Arguably, the fascination triggered by dynamic visualizations is due to the basic fact that they show elements in motion. As a consequence, instructional materials that use animation or video can include rich temporal and spatial information that is generally absent in static images or textual resources. For example, the following learning opportunities can be provided with instruction aided by dynamic visualizations:

- To change the pace of real-time phenomena whose speed/duration is impractical to study live. For example, very slow processes can be speeded up, and very fast processes can be slowed down (Tosi, 1993).
- To analyze the same dynamic event repeatedly, or to preserve permanently a rare live phenomenon (Tosi, 1993).
- To study dynamic processes in unapproachable places, such as inside a living organism, in outer space, in extreme habitat conditions (Tosi, 1993), or in rather avoidable situations (Dowrick, 1991).
- To perceive movement or details that in real-life motion would be overlooked. For example, the video technique of reverse motion (e.g., Dowrick, 1991) can help to study bodily processes. In addition, different video editing methods can be employed to study *movement* in art disciplines (e.g., Nadaner, 2008).
- To watch otherwise invisible events, by using X-rays, infrared, gamma, ultraviolet techniques, and many others (Tosi, 1993). Similarly, dynamic visualizations can assist in explaining not inherently visible phenomena, such as electrical circulation or energy (Bétrancourt, 2005).
- To compare simultaneously two or more dynamic processes by splitting the screen accordingly. This can be a valuable tool in science learning, where a concrete video can be juxtaposed to an abstract molecular animation (e.g., Nugteren, Tabbers, Scheiter, & Paas, 2014), and also to study performing arts, such as dance (e.g., Harris & Fenner, 1995), where different parts of the dancer can be analyzed simultaneously.

Table 1 Examples of STEAM contents depicted in studies about dynamic visualizations

Study	Discipline					Content
	S	T	E	A	M	
Dorethy, 1973				x		Visual analysis of space
Shipley, Butt, Horwitz, & Farbry, 1978	x					Patient getting an endoscopy
Rieber, 1990	x					Newton's laws of motion
Mayer & Sims, 1994	x					Human respiratory apparatus
Harris & Fenner, 1995				x		Choreographic dancing
Williamson & Abraham, 1995	x					Chemistry reactions
Lowe, 2003	x					Weather map sequences
Yang, Andre, Greenbowe, & Tibell, 2003	x					Electrochemistry in a flashlight
Stith, 2004	x					Cell apoptosis
Mayer, Hegarty, Mayer, & Campbell, 2005			x			Brakes and flushing systems
Cooley, 2007				x		Audiovisual poetry
Boucheix, 2008			x			Gear systems
Kalyuga, 2008					x	Linear and quadratic functions
Fischer, Lowe, & Schwan, 2008			x			Mechanism of pendulum clock
Marbach-Ad, Rotbain, & Stavy, 2008	x					Protein synthesis
Nadaner, 2008				x		Perception of movement
Boucheix & Lowe, 2010			x			Piano elements kinematics
Huk, Steinke, & Floto, 2010	x					Enzyme ATP-synthase
Linek, Gerjets, & Scheiter, 2010					x	Probability calculations
Meyer, Rasch, & Schnotz, 2010			x			Internal combustion engine
Scheiter, Gerjets, & Schuh, 2010					x	Algebraic worked-out examples
Yarden & Yarden, 2010	x					PCR method in biotechnology
Höffler & Schwartz, 2011	x					Surfactants and washing
Lin & Atkinson, 2011	x					The rock cycle
Ryoo & Linn, 2012	x					Energy flow in photosynthesis
Brucker, Scheiter, & Gerjets, 2014	x					Fish swimming patterns
Sánchez & Wiley, 2014	x					Plate tectonics

These instructional opportunities have been applied to teach various concepts of Science, Technology, Engineering, Arts and Mathematics (STEAM) disciplines. Significant research has been conducted into dynamic images and a wide variety of STEAM topics to provide evidence for the effectiveness of such instructional visualizations. Table 1 provides a sample of this research, where the studies are listed chronologically.

In addition to the learning opportunities and the interest that dynamic visualizations can trigger, these depictions are increasingly easier to produce, replicate and disseminate for instructional purposes. However, despite potential educational advantages, dynamic pictures can be very problematic learning materials if they are heavily reliant on *transient information*. The negative effect of transient information has been observed in experiments that show poorer learning outcomes after receiving long verbal passages in auditory rather than in textual forms (e.g., Leahy & Sweller, 2011; Singh, Marcus, & Ayres, 2012). As discussed by Leahy and Sweller

(2011), students cannot easily review transient information (auditory passages), but permanent information (textual passages) can be re-read at convenience. An analogous phenomenon has been described for dynamic versus static visualizations.

Transiency of Dynamic Visualizations

A dynamic visualization is composed of a number of different static images (frames) that are played at a sufficient speed to give the illusion of dynamism (Roncarrelli, 1989). The illusion of movement can generally be achieved with approximately 12 frames per second. As a consequence, a dynamic visualization can generate transient effects as information can change rapidly from frame to frame. This problematic phenomenon has been termed as the *transient information effect of animations* (see Ayres & Paas, 2007a, b). As a result, dynamic pictures may impose extra processing burdens on students' working memory; what Lowe (2003) described as an *overwhelming* effect. Particularly, as discussed by Ayres and Paas (2007b) and van Gog, Paas, Marcus, Ayres, & Sweller (2009), students may have to perform three mental activities in order to learn from a dynamic visualization: (a) observing the current information depicted, (b) memorizing the important depictions no longer shown, and (c) combining these two streams of information. By contrast, a static visualization, which is permanent and thus can be reexamined repeatedly if necessary, is much less cognitive demanding, and consequently more working memory resources are available for learning (see *cognitive load theory* in Sweller, Ayres, & Kalyuga, 2011).

Consequently, static visualizations often show better learning outcomes than comparable dynamic pictures. This trend has been observed with many STEAM concepts. For example, when Koroghlanian and Klein (2004) studied learning outcomes for the concepts of mitosis and meiosis in high-school biology students, they observed that the animation conditions required more time to learn than the statics groups, without an increase in performance. Similarly, Mayer et al., (2005) compared *static images plus text* versus *narrated animations* as learning tools for the mechanisms of toilet tanks, lightning formation, cars brakes and ocean waves, and observed that the participants studying static pictures outperformed those given dynamic visualizations. Also, Scheiter, Gerjets, and Catrambone (2006) compared the effects of appending static versus dynamic visualizations to texts about probability theory, and found that, compared to the text-only materials, adding statics improved performance but adding dynamic pictures hindered learning outcomes. In contrast, there is research showing better outcomes from dynamic rather than static pictures, with STEAM disciplines such as physics (e.g., Rieber, 1990), cellular biology (e.g., Stith, 2004), chemistry (e.g., Ardac & Akaygun, 2005), and visual arts (e.g., Dorethy, 1973).

Nevertheless, some questions have been raised about the validity of the controls in experiments comparing statics with animated materials. Tversky, Morrison, and Betrancourt (2002) argue that the animation advantage found in some studies could be due to additional information contained within the dynamic images, which is not replicated in the static resources. In spite of the often conflicting results when dynamic visualizations are compared to static images, and the different theories proposed in support of this research, evidence is accumulating that transient information is a major impediment to learning from dynamic pictures (see Ayres & Paas, 2007a; Sweller et al., 2011; see also Castro-Alonso, Ayres, & Paas, 2014b). Hence, much recent research has focused on finding strategies to deal with transient information contained within dynamic visualizations (see Castro-Alonso, Ayres, & Paas, 2014a).

Overcoming the Transiency of Dynamic Visualizations

One straightforward strategy to manage the transient information of some dynamic images is to include in these resources a pause facility, which makes the animation/video more permanent by stopping it, thus giving the learner extra time to memorize the important depictions if necessary. This strategy is often referred to as *pace-control*—also known as *stepwise, self-pacing*, or *learner-controlled*— where learners can manage the transitory nature of the dynamic depiction by simply pausing the presentation. Researchers have predicted that pace-controlled animations should be better instructional materials than *continuous* or *system-controlled* versions (see Ayres & Paas, 2007a; Mayer, 2008; Schnotz & Rasch, 2008). Supporting evidence comes from Höffler and Schwartz (2011), who found that pace-controlled groups outperformed and reported less working memory demands than system-controlled conditions in a study where university students had to learn about chemical dirt removal. Similarly, Mayer and Chandler (2001) observed that learners who studied the formation of lightning from a self-pacing animation presented higher transfer scores than those studying from the continuous version of the visualization. Also, Hasler, Kersten, and Sweller (2007) found a learner-controlled advantage in a study with primary school students learning about the causes of day and night. As these studies show, the pace-control strategy gives the learners opportunities to interact with the depictions. However, further discussion of the additional advantages of interactivity (e.g., in simulations and virtual models; see Moreno & Mayer, 2007) is beyond the main focus of this chapter.

Another strategy to deal with transitory visualizations is *segmenting*. This method consists of segmenting whole animations into shorter parts that are not as cognitive demanding as the total block (Moreno, 2007). A prediction that follows this strategy is that segmented dynamic visualizations should be better instructional resources than whole dynamic visualizations (Ayres & Paas, 2007a). A supporting example is the previously mentioned experiment by Hasler et al. (2007) that compared learner- versus system-controlled animations, which also included a segmented version in the comparison. The study found that learner-controlled and segmented animations were equally effective, and that both outperformed the system-controlled whole version. Similar findings supporting both pace-control and segmenting strategies were reported by Spanjers, van Gog, Wouters, and van Merriënboer (2012) with animations depicting probability calculation tasks.

Finally, a third strategy is signaling—also named *attention-guiding* (e.g., Bétrancourt, 2005) or *attention cueing* (e.g., de Koning, Tabbers, Rikers, & Paas, 2009). It is predicted that a student will learn better if cues are added to the dynamic visualizations, which signals the relevant information and thus avoids disorientation (for a review, see Mayer, 2008). Although this technique does not prevent a negative transitory effect directly, it prevents learners' disorientation when depictions are showing multiple elements continuously changing. Examples of this technique include arrows and texts, which have been employed effectively as signals in scientific animations that depict (a) the rock cycle (Lin & Atkinson, 2011), (b) gear systems (Boucheix, 2008), or (c) an enzyme's structure and function (Huk et al., 2010). Similarly, signals such as giving more luminance or color to the important elements have been added to animations that show the cardiovascular system (e.g., de Koning, Tabbers, Rikers, & Paas, 2010).

In contrast to these encouraging results that support strategies to overcome the transiency of dynamic pictures, there are also conflicting findings or inconclusive outcomes, which are mainly found in the pace-control strategy (e.g., Boucheix, 2008; Kriz & Hegarty, 2007; Tabbers & de Koeijer, 2010). Boucheix (2008) provides an explanation, which especially applies for low spatial ability learners self-controlling a dynamic image: When these students are constantly observing the controls to pause/play the dynamic visualizations, they are diverting their attention away from the important elements shown in the depictions.

Although identification of the transient information effect on dynamic visualizations has made—and continues to make—a contribution to the field, the complex nature of computer-based learning means that more than one category of strategies is required to create optimum learning environments. Hence, researchers must explore new directions. One promising direction outlined in this chapter is *embodied cognition*, which entails a relatively new approach to the study of cognitive processes.

The Embodied Cognition Perspective

Even though the traditional views of cognition (e.g., Atkinson & Shiffrin, 1968; Simon & Gilmartin, 1973) tend to describe mental processes as centralized and independent of the peripheral body, a more current embodied, or grounded cognition perspective (see Barsalou, 2010) acknowledges the connection between the mind to the rest of the body and to their common natural habitat. As suggested by Wilson (2002), humans have evolved an embodied cognition because they originally had to persist in continuous interactions between their mind, bodies and environment, in order to avoid death. Wilson refers to this cognition as *on-line*, because it is a mental activity connected always to its inputs and outputs. Then, after many millennia, civilization reduced the survival threats, so human mental processes were able to further employ *off-line* abstract cognition, which was more independent of the perceptual and motoric (related to muscle movement) elements that allow interactions between the mind, body, and the environment. However, even the most abstract process of contemporary human cognition can profit from embodied experiences, since cognition has evolved a foundation in sensorimotor processing that connects the mind's perception and action streams (Wilson, 2002).

The embodied nature of cognition has been observed in studies that show how visual perception interacts with the motor system, particularly during object manipulation (e.g., Chao & Martin, 2000; Witt, Kemmerer, Linkenauger, & Culham, 2010). Moreover, attention and memory for abstract depictions can be enhanced by showing hands reaching these elements (see Brockmole, Davoli, Abrams, & Witt, 2013; see also Weidler & Abrams, 2014). Extending these findings, some of the abstract STEAM concepts could be facilitated by showing hand movements, such as *manipulations* and *gesturing*. This endorsement of using on-line evolved skills (in this case, manipulations and gesturing) to teach off-line skills (in this case, STEAM concepts) is arguably the main goal of *evolutionary educational psychology*.

Evolutionary Educational Psychology

Recognizing facial expressions, employing physical materials as tools, inferring the intention of other individuals, and understanding gestures can all be considered rather uncomplicated tasks for humans, as we have evolved those skills over countless generations (Geary, 2002). The *Homo sapiens* species has had several millennia, and thus opportunities, to evolve or refine, for example, the skill of gesturing. This implies that we evolved an embodied cognition, appropriate to process the particular information that is involved in making and observing gestures (Geary, 2007). Therefore, gesturing is an ability that evolved because it helped us to establish advantageous relationships to access essential supplies for our species (Geary, 2002). Similarly, every other skill that was beneficial for the survival of our ancestors, such as object manipulation, should have evolved to be a relatively effortless ability today (Geary, 2007). Thus, these skills have been termed by evolutionary educational psychology researchers as *biologically primary abilities* (Geary, 1995).

In contrast to the skills shaped by evolution, there are *biologically secondary abilities*, which are shaped by a more current force: human culture (Geary, 1995). Examples of these abilities are reading, solving mathematical problems, learning to use novel instruments, and studying various science concepts (e.g., energy, force, and mitosis). Moreover, most of the school syllabi and STEAM instruction concerns biologically secondary abilities. The acquisition of this secondary knowledge is slower and more effortful than the attainment of the evolved skills (Geary, 1995). However, both are equally required to "survive" in a civilized society where primary knowledge is no longer sufficient (Geary, 2002). In consequence, the schooling system emerged to teach these necessary but effortful abilities.

Considering the greater difficulty to learn secondary abilities, Geary (2002) claims that primary knowledge should be used as a vehicle for learning secondary knowledge. In support of this view, for example, Paas and Sweller (2012) argue that the relatively easy acquisition of two primary abilities, object manipulation and gesturing, can assist the learning of the more difficult secondary skills of formal instruction. In addition, when dealing with secondary abilities that are even more challenging because they are presented with transient visualizations, the rationale to use primary skills in this case becomes more apparent (see *the human movement effect* in Paas & Sweller, 2012). As described in Section "Embodied Dynamic Visualizations for STEAM Instruction", research around the human movement effect shows a relatively new embodied strategy to facilitate learning of STEAM topics via dynamic visualizations.

In conclusion, evolution shaped the human brain to learn certain biologically primary abilities more easily than the non-evolved secondary knowledge. In other words, there are cognitive systems evolved to deal with primary abilities. For example, the *mirror neuron system* (for a review, see Rizzolatti & Craighero, 2004) is arguably the most important cognitive processor that has evolved to deal with the imitation of human manipulation and gesturing.

The Mirror Neuron System

Mirror neurons were firstly described by di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti (1992), who observed these nerve cells in the brain's premotor cortex of macaques (*Macaca nemestrina*). The authors named these cells as *mirror neurons* because they were triggered (a) when the animals directly performed certain hand actions, such as grasping and manipulating objects; and also (b) when the macaques observed the same actions being performed by the human experimenters. Fadiga, Fogassi, Pavesi, and Rizzolatti (1995) extended the mirror neuron phenomenon to humans by recording responses from a number of forearm and hand muscles. The pattern of muscle contraction observed in the participants when they performed certain arm and hand actions was very similar to the pattern recorded when they observed the same movements executed by the experimenter.

In humans, the mirror neurons constitute a system that has an extensive brain distribution over the premotor, parietal, and subcortical areas (Cross, Hamilton, & Grafton, 2006). In other words, the mirror neuron system is connected to brain areas that participate in embodied activities of perception and action for hand tasks. These systems have evolved to help humans manage the information associated with manipulation and gesturing, and it is believed that these processors are mainly triggered during natural manipulation and gesturing conditions. In contrast, phenomena not associated with human evolution are less likely to activate the mirror neurons and related action–recognition systems. This rationale has been supported by findings where the observation of robotic hand or arm actions has led to smaller (e.g., Press, Bird, Flach, & Heyes, 2005) or non-significant effects (e.g., Kilner, Paulignan, & Blakemore, 2003) on the observer's motoric system, as compared to the observation of human limbs performing the movements. Analogously, Järveläinen, Schürmann, Avikainen, & Hari (2001) reported that the motor cortex of their participants was more strongly triggered when they watched live human hand movements as compared to the same video recorded actions. Finally, Shimada and Oki (2012) showed that an area of the mirror neuron system was activated more when the participants watched an animated character's arm doing natural continuous movements rather than jerky and paused motions. Thus, because *biological, live*, and *continuous* hand actions coevolved with embodied systems, these actions may activate the mirror neuron system more strongly than *artificial, recorded*, and *jerky* hand movements.

Nevertheless, the previous findings do not imply that any non-natural phenomenon will be ineffective in triggering cognition. Such a radically embodied approach would lead to the erroneous rejection of all technological (non-natural) solutions in instruction. For example, animated or video recorded hand actions could be regarded as futile approaches to deal with problematic STEAM concepts. However, although artificially (video) observed hand actions may trigger brain processors to a smaller extent than live actions (e.g., Järveläinen et al., 2001), Rohbanfard and Proteau (2013) showed that such artificial methods were still productive for learning a sequential timing hand task. In addition, there is accumulating research showing that object manipulations and gestures are important in learning from complex dynamic visualizations, as described next.

Embodied Dynamic Visualizations for STEAM Instruction

Characterizing the human movement effect, Paas and Sweller (2012) predicted that evolved embodied systems could help to manage problematic learning materials, in particular instructional animations and videos conveying transient information. Moreover, because evolved mechanisms such as the mirror neuron system are triggered more with fluent movement (e.g., Shimada & Oki, 2012), it could be expected that dynamic visualizations of manipulations and gesturing would show better learning outcomes than their static equivalents. Hence, the problem of transiency in these specific dynamic visualizations could be overcome by the greater activation of evolved cognitive systems. This has huge potential for STEAM instruction, where human manipulations and gestures could be used as part of the dynamic visualizations in these disciplines.

It is worth noting that both a dynamic visualization of an object manipulation and that of a gesture share the property of showing human hand actions. The main contrast between manipulations and gestures is their different dependency on manipulable objects (cf. Ping, Goldin-Meadow, & Beilock, 2014). Manipulations need to show the manipulatives, which is less mandatory with gesturing. For example, it has been reported that the effectiveness of showing gestures is not hampered when the corresponding objects are not depicted (Ping & Goldin-Meadow, 2010). Conversely, gestures need to show the hands, which is less compulsory with manipulations. For example, the effectiveness of showing a manipulation may not be hindered when the corresponding hands are not depicted, provided that the objects are manipulative enough to trigger by themselves the positive embodied effects (e.g., Wong et al., 2009). This difference among visualizations of human hand actions is shown in Fig. 1 (top).

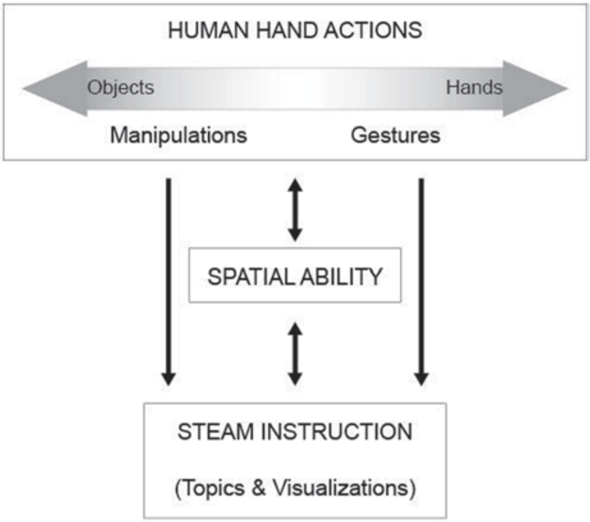

Fig. 1 Interrelationship between human hand actions (manipulations and gestures), spatial ability, and STEAM instruction (STEAM topics and STEAM visualizations). The arrows show beneficial relationships

The depiction of hand actions—manipulations and gestures—can be effectively employed in any kind of dynamic visualization of STEAM topics, such as movies, animations, simulations, and videos. One example of video and object manipulation concerns the biological concept that the cell membrane is a fluid mosaic, which can be illustrated with a video that shows the teacher manipulating different balls (representing proteins and lipids) in a tray with water (Miller, 1998). One example of animation and gesture is about the meteorological concept of lightning formation, which can be instructed with an animation that includes a dynamic pointing hand that constantly signals the relevant elements (de Koning & Tabbers, 2013).

Manipulations and gestures will be described separately in this section, focusing on their use in STEAM dynamic visualizations. Subsequently, spatial ability, important to understanding manipulations and gestures, is described at the end of this section. Note that the focus on this chapter is not in the beneficial effects of performing hand actions, but on observing them as manipulations and gestures. Accordingly, the execution of hand actions, whether directly or via interactive simulations, will only be briefly addressed.

Manipulations in Dynamic Visualizations

It was mentioned previously that, as compared to static pictures, dynamic visualizations show more promise as learning tools for human motor skills (for a review, see Castro-Alonso et al., 2014a). For example, the review by Park and Hopkins (1992) that searched for instructional purposes for animations concluded that dynamic visualizations were most effectively employed for human actions that followed a procedure. Similarly, Höffler and Leutner (2007) reported that the largest differences favoring dynamic over static images were observed when the depictions showed procedural skills.

Moreover, growing research suggests that manipulative–procedural tasks are better portrayed in animation or video rather than in static images. A classical study was conducted by Spangenberg (1973), in which the task of disassembling a machine gun was compared between a group that watched the steps though video versus the conditions that studied the steps though equivalent static images. The procedure was better executed by the video conditions. Note that, as it is fundamental for this dynamic versus statics comparisons, Spangenberg used the same medium (television) to deliver both video and still images. Similarly, Michas and Berry (2000) compared equivalent video versus video stills conditions in learning to apply a bandage to a wounded hand. Here, the video condition outperformed the still group in bandaging performance and test retention scores. Also in controlled between-subjects experimental conditions, Ayres, Marcus, Chan, and Qian (2009) observed that the animation groups presented higher cognitive and transfer results than the statics, where the manipulations involved solving hand-puzzle rings and replicating knots. In addition, for other knot tying tasks, research has shown better performance associated to animated rather than to static learning presentations (Garland & Sánchez, 2013; Marcus, Cleary, Wong & Ayres, 2013). Interestingly, Garland and Sánchez (2013) also compared performance between two dynamic conditions that differed in viewing angles. The video with the perspective that supposedly elicited more of the mirror neuron system (over-the-shoulder, first person view) was a better learning tool than the video with the angle that activated less of this embodied system (face-to-face, third person view). A further example of animation outscoring static images was reported in a study using paper-folding tasks by Wong et al. (2009). Also notable in this study was that when the manipulative folding task was replaced by a non-manipulative task, dynamic images were no longer superior to statics, indicating that the human movement effect may had disappeared and transiency could not be handled as efficiently. Altogether, these findings support the human movement effect due to embodied mechanisms (such as the mirron neuron system, see van Gog et al., 2009), and suggest that dynamic images should be favored over statics when learning procedural and manipulative tasks.

Although the previous studies about dynamic visualizations of manipulatives could be easily applied to the Technology or Arts disciplines, the literature is scarce for the other branches of STEAM. For example, in Science and Mathematics, manipulative learning rarely entails observation of the manipulations through visualizations, but rather the direct manipulation of real objects or virtual models. Thus, research of manipulations to instruct a wide range of STEAM concepts through visualizations is not abundant. However, we argue here that, due to the embodied mirror mechanisms, some of the effects of direct manipulations could also apply when observing others (e.g., teachers) doing the manipulations in video or animation. Consequently, the gathered evidence about direct manipulations to learn STEAM concepts (e.g., Manches, O'Malley & Benford, 2010; Miller, 1998; Zacharia & Olympiou, 2011) could be applied to instructional dynamic visualizations depicting manipulations. Likewise, the remaining discussion of this subsection, which focuses on manipulations performed by the learners, could be applied in future research about visualizations that show manipulations.

Because, as commented above, the main depiction of a manipulation is the manipulative object, research has focused on the *type of object* used, for example, whether the element is rather *concrete* or *abstract*. Since STEAM concepts are largely based on underlying mechanisms, as opposed to readily visual relations, objects that imply these mechanisms—abstract—instead of showing much visual information—concrete—tend to be preferred (e.g., Brown, McNeil & Glenberg, 2009; Kaminski, Sloutsky & Heckler, 2009; but see Sowell, 1989), as the rich information of concrete elements may distract attention from the more relevant but underlying STEAM principles. Although this seems to suggest that concrete type of objects should be discarded, Fyfe, McNeil, Son, and Goldstone (2014) proposed a less radical mixed strategy of three connected steps, from concrete to abstract manipulatives, which benefits both from the concrete object (embodied perceptual and motoric experiences) and from the abstract model (without distracting features, better to understand and transfer the concept). Altogether, it seems that mixed dynamic visualizations that include both concrete and abstract objects should be fostered to understand STEAM concepts.

In addition to the type of object, there is also another differentiation of manipulatives. This new dimension respects the *type of environment* for the manipulation, which distinguishes between *physical* (real objects moved by physical hands) versus *virtual* (virtual replicas of the objects being moved by the mouse, keyboard, etc.). In a review of controlled experiments, de Jong, Linn, and Zacharia (2013) concluded that both physical and virtual manipulatives were equally successful for acquiring different science concepts. However, a promising new approach instead of comparing both type of environments, is to mix these scenarios (see de Jong et al., 2013), similarly to the blended method with type of manipulative. Furthermore, recent technologies of *mixed reality* (see Lindgren & Johnson-Glenberg, 2013), which allow real hands to manipulate virtual objects, are blurring the boundaries between physical and virtual environments.

In short, when designing manipulative tasks for dynamic visualizations, mixed approaches of the type of manipulative (concrete and abstract) and the type of environment (physical and virtual) are advisable. Arguably, other instructional methods that use embodied visualizations could benefit from mixed approaches, such as showing both physical and virtual hands in depictions of gestures.

Gestures in Dynamic Visualizations

Because gesturing is an evolved primary skill, diverse evidence illustrate how easily or pervasively it is acquired by humans: (a) children can gesture before speaking, and they gesture to convey information not already in a verbal state (e.g., Goldin-Meadow & Wagner, 2005); (b) gestures get so integrated to the concurrent speech, that it is difficult to determine whether the information was given verbally or by gestures (e.g., Kelly & Church, 1998; McNeill, Cassell & McCullough, 1994); and (c) when doing motoric actions while observing gestures, the speed in responding to the message is hampered, suggesting that the motor system of the observant is activated to understand gestures (Ping et al., 2014). Thus, gestures are embodied and evolved human communicative skills that, as human manipulations, can be effective educational means to learn new concepts.

Evidence is accumulating that gesturing may be very important in STEAM instruction. For example, it has been shown that when students are allowed to gesture while explaining their solutions to mathematical problems, this embodied activity frees cognitive capacity to deal with secondary memory tasks (Goldin-Meadow, Nusbaum, Kelly & Wagner, 2001). Also, in addition to performing gestures, direct observation of these hand signals has also proven effective in mathematics instruction. For instance, Richland, Zur, and Holyoak (2007) analyzed use of analogies by mathematics eighth-grade teachers in USA, Hong Kong and Japan. One of the findings that the authors linked to better standardized-test performances in both Asian countries was that Hong Kong and Japan teachers used significantly more hand or arm gestures than USA instructors in connecting source analogs with their targets.

However, more pertinent to the focus of this chapter is the effect that the observation of gestures via dynamic visualizations has on instruction. A classic study on this topic was conducted by Riseborough (1981), who reported the benefits of including gestures when presenting verbal information via video. In the tasks of guessing an object that was described, recalling different verbs from an oral list, or remembering important words from a short story, Riseborough (1981) found better outcomes in the participants in the gesture conditions, as compared to no movements or vague movements conditions. Similarly, Church, Ayman-Nolley, and Mahootian (2004) reported that the concept of Piagetian conservation was better understood by elementary grade children who learnt from a video with speech plus gestures as compared to children that watched the speech only video. Interestingly, the main objective of this study was to find the effects that the observation of gestures on video could have in students with a poor English knowledge. In other words, Church et al. investigated how gestures would affect learning a mathematical concept when the capacity to verbally understand the concept was diminished. The authors found that the number of non-English speakers who understood the concept of conservation via speech and gestures was more than double the number of those who learnt without gestures. Another study about the benefits of dynamic visualizations depicting gestures was conducted by Valenzeno, Alibali, and Klatzky (2003) on preschool children studying a video about the concept of bilateral symmetry. The authors observed that the participants in the speech with gestures video condition gave more advanced and frequent explanations about symmetry than the children in the speech only condition. Kang, Hallman, Son, and Black (2013) showed that, for adults learning the biological concept of mitosis, the participants who studied a video with the instructor providing spoken explanations and meaningful gestures gained a deeper understanding of mitosis than those who observed a video with the instructor giving spoken explanations without showing the hands (non-gesturing condition). Hence, several examples with diverse students and STEAM contents show more positive learning outcomes after studying from audiovisuals with gestures than from equivalent depictions with only speech and not gestures.

Regarding the underlying causes for these favorable effects of dynamic images with gestures, there are three non-mutually exclusive mechanisms to consider (cf. Valenzeno et al., 2003). Firstly, as discussed above, videos and animations with gestures activate embodied mechanisms, and also relate abstract concepts to the real physical environment. Secondly, dynamic depictions showing gestures capture students' attention better than those without these motions, as Valenzeno et al. (2003) found with preschool students. And thirdly, gestures provide an additional informational channel, simultaneous to the verbal channel being used in speech, thus conveying supplementary data to the learner.

However, this same advantage of providing more information could result in the unfavorable effect of providing unnecessary redundant information (see *the redundancy principle* in Sweller, 2005). In other words, showing hands performing gestures adds more depictions than are needed to learn a task, which might distract instead of foster learning (e.g., Castro-Alonso et al., 2014b). This is particularly evident when gestures are not *representational*, thus, they do not convey meaning. For example, Riseborough (1981) measured word recall from a verb list or a short story delivered through videos. In contrast to the significant positive effects of showing meaningful gestures when narrating the words, only a slight benefit was found for vague movements compared to no movement at all. Similarly, Kang et al. (2013) reported no advantages of *beat gestures*—which only stress speech elements but do not convey meaning—when learning the concept of mitosis, in contrast to representational gestures. Thus, as Kang et al. suggested, gestures in dynamic visualizations should mean something, rather than being just hand movements with no clear representation, as this latter scenario may even hamper learning.

Embodied Spatial Ability

We have described above the potential for using manipulations and gestures in dynamic visualizations. However, the capability to understand both is aided by *spatial ability*. In a meta-analysis, Linn and Petersen (1985) defined spatial ability as a skill to represent, transform and generate non-verbal information. In addition to helping learn human hand actions, spatial ability is very important for learning STEAM topics (see this central role of spatial ability in Fig. 1). For example, after analyzing a dataset of approximately 400,000 high-school students in their progress through Bachelors, Masters and Doctorates degrees, Wai, Lubinski, and Benbow (2009) reported that spatial ability was always higher than verbal ability (but lower than mathematical ability) for those in the disciplines of Math/Computer Science, Physical Science, and Engineering.

Moreover, spatial ability is fundamental to studying from video and animation. For example, Höffler (2010) showed in his meta-analysis that spatial ability was an essential capacity in learning from dynamic and static visualizations. In other words, spatial ability not only can aid the learning of STEAM topics, but also of STEAM visualizations, what implies that it is very beneficial for understanding STEAM instruction. Also, as shown in Fig. 1, the opposite applies and STEM instruction is very advantageous to boost spatial ability (e.g., Lord, 1990; Pallrand & Seeber, 1984; Stransky, Wilcox, & Dubrowski, 2010). In consequence, increasing spatial abilities in students (e.g., Baenninger & Newcombe, 1989; Yang & Chen, 2010) could be an effective instructional approach.

Spatial ability is a construct that can be divided into subfactors, one of which is *mental rotation* (e.g., Linn & Petersen, 1985)—sometimes referred to as *spatial relations* (e.g., Höffler, 2010). In arguably the seminal study of mental rotation, Shepard and Metzler (1971) asked participants to compare pairs of three-dimensional figures made with cubes, in order to determine if each pair showed either (a) the same figures, but rotated differently; or (b) different figures, meaning that they were not only rotated but also reflected. Shepard and Metzler observed that the reaction times to determine the correct answer (*same* or *different* configuration) were linearly correlated with the angular differences between the pair of figures.

The fact that smaller angles implied faster mental rotations has been proposed as a connection between mental and actual physical rotation (see Cooper, 1976; Janczyk, Pfister, Crognale & Kunde, 2012). In other words, spatial ability, and particularly mental rotation, can also be regarded as an embodied cognitive process. For example, a number of findings have shown a link between mental rotation and embodied mechanisms (see Krüger, Amorim & Ebersbach, 2014). Furthermore, the extent of the embodiment of mental rotation has been observed with both manipulation and gesturing tasks. For instance, Wexler, Kosslyn, and Berthoz (1998) reported a strong link between mental and simultaneous manual rotation of two-dimensional figures. Interestingly, the interaction between the mental and motoric turning of the figures was affected by the direction, speed and final position of both the mental and the manipulative rotation. Similarly, Janczyk et al. (2012) showed that a mental rotation task positively influenced a following manual rotation task in the same gyratory direction. Regarding gestures, Chu and Kita (2011) observed that students who were encouraged to gesture in order to solve difficult three-dimensional rotation tasks outperformed the participants restrained from gesturing. Moreover, this gesturing effect was transferred to subsequent spatial ability tasks where gesturing was no longer allowed, showing that the positive effects of these hand movements extended over time. A last noteworthy finding in this study was that, as expertise to solve the mental rotations increased, gesturing frequency decreased, arguably because the spatial processes supported by embodiment had become internalized. These embodied effects of spatial ability suggest that this ability is not only important to learn human hand actions, but that the reverse is also true: Human hand actions, such as manipulations and gestures, are helpful in tasks that demand spatial ability (see Fig. 1). In addition—as the research reported in this chapter suggests—these human hand actions are very relevant for STEAM instruction.

Implications for Instruction

From the wide variety of STEAM topics that could benefit from instructional dynamic visualization showing manipulations, we provide two specific examples. For the concept of photosynthesis in biology, all the agents involved (sun, energy, water, etc.) and their relationships could be written or drawn on different pieces of paper, and these paper notes could be manipulated in a video with auditory explanations. So, for example, the teacher could be video-recorded manipulating a piece of paper with the word *energy* written on it, and moving it toward another piece representing *leaf*, while explaining that the *energy of the sun is received by the leaf*. For arithmetic concepts in mathematics, animations of virtual fingers moving squares from one group to another could help understand the computations involved. For example, a simple addition such as $1+1=2$, could be represented by two animated fingers moving a square each with the number *1* written on it, and placing them together to form a combination labeled as *2*. In general, when designing manipulations for a dynamic visualization, consider also that blended methods, which mix type of objects (concrete vs. abstract) and/or type of environments (physical vs. virtual), may be more effective.

For dynamic visualizations of gestures, we also provide two examples. To solve linear equations, a video of a moving hand can be very effective in showing that certain operations can be represented by moving the various variables from one side of the equation to the other. In music education, animations of static hands in different states (open, fist, etc.) can represent the different duration of musical notes. When designing gestures for a dynamic visualization, it is important to note that gestures should convey meaning and not include meaningless hand movements.

A number of additional implications for the design of STEAM animated or static visualizations follow:

- Due to transiency conveyed in dynamic visualizations, static images may sometimes be better resources for learning. Similarly, due to the transient information effect, dynamic visualizations that include methods to overcome the transiency (e.g., pace-control, segmenting, or signaling) may be more effective than animations and videos that do not use these strategies.
- Because spatial ability plays such a critical role, it is also highly recommended that learners' spatial ability should be developed independently or as part of STEAM instruction.

Future Directions for Research

We consider four interesting directions for further research about embodied dynamic visualizations for STEAM instruction. Firstly, provided that both manipulation and gestures are similar mechanisms that depict hand actions, their differential dependency to either manipulative objects or hands could be further investigated. That is, one direction for future research is to continue investigating the impact of object manipulations when the hands are depicted or not shown in the visualizations. Similarly, another future direction is to compare the effectiveness of gesturing when the corresponding objects are shown or not shown.

Secondly, the majority of research on manipulative tasks involves direct manipulations by the learners, either physically or virtually. Future studies could investigate the more indirect effect of observing STEAM dynamic visualizations depicting real or virtual manipulations. These studies could benefit from the effective instructional applications that have been reported for direct manipulations. Also, this direction could widen the research on the mirror neuron system by comparing performing hand actions versus only observing these actions.

Thirdly, the studies on visualizations of manipulative tasks and gestures need to broaden their scope to include concepts from more diverse disciplines. Indeed, much of the reported manipulative dynamic visualizations could be connected to Technology or Arts; similarly, gesturing visualizations tend to focus on Mathematics. Thus, the Science and Engineering branches of STEAM seem to be underrepresented in these investigations. Similarly, other educational areas, such as Language, could be equally benefited by the visualization of human hand actions.

Finally, the human movement effect and its impact on dynamic versus static images have been shown for many manipulative tasks, but not many for gesturing. In that sense, a step forward would be to compare the learning effectiveness of static or dynamic STEAM visualizations that include gestures.

Conclusion

Although dynamic visualizations are increasingly more appealing and easier to produce, and can be linked to gaming applications and high motivation, their benefits may be counterbalanced by the problematic transient information that they can convey. Beyond three popular methods to manage this transient information, we recommend a relatively newer approach from the embodied cognition research: the use of the embodied evolved skills of manipulation and gesturing. The new research reported in this chapter provides more evidence that the embodied cognition perspective, in the form of manipulations and gestures, has a great potential to enhance the use of both dynamic and static visualizations for STEAM topics. However, it is important to note that spatial ability is a factor that must be considered. Not only does it moderate the effectiveness of learning from dynamic and static representations, but it is also a crucial factor in the capacity to learn many STEAM concepts.

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