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REGULAR ARTICLE

Gestures Enhance Executive Functions for the Understating of Mathematical Concepts

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Abstract
This article discusses the role of gestures in enhancing inhibition, working memory, and cognitive flexibility as the three components of executive functions during the processing of mathematical concepts that are metaphorically described in terms of motion events. Gestures can contribute to the process of inhibition by highlighting the relevant information and keeping the irrelevant information out of focus of attention. Gestures contribute to working memory in two ways during mathematical processing. They increase activity in the motor areas of the brain. Therefore, they may facilitate the process of understanding those mathematical concepts that are described in terms of motion event, as the motor system could play a role in the grounding and the processing of these concepts. Also, gestures can function as an external working memory and keep the visual representation of some parts of information for a short period of time in order to manipulate that information in later stages of processing. Gestures enhance cognitive flexibility by allowing us to have a spatial representation of that concept or idea for a period of time. During this time, we can shift our perspective and process that concept or idea from a variety of perspectives.

Keywords Gestures · Executive functions · Mathematical concepts · Embodied cognition

Introduction

The role of gesture in the processing of concepts has been the subject of a large body of research (e.g., Johnson-Glenberg & Megowan-Romanowicz, 2017; Macedonia, 2019; Yeo et al., 2017; Radford, 2003). Some works have supported the idea that gestures play a causal role in the process of learning new material and the develop-

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ment of knowledge (e.g., Alibali & Kita, 2010; Goldin-Meadow et al., 2008; Radford, 2009; Singer et al., 2008). Discussing the self-regulatory cognitive functions of gesture, Kita et al., (2017) argue that representational gestures (iconic and metaphoric gestures) enhance cognitive processes by activating, manipulating, packaging, and exploring spatio-motoric information for speaking and thinking. There is some evidence that suggests gestures can play a self-regulatory role not only for adults but also for very young children (e.g., Basilio & Rodríguez, 2017; Moreno-Núñez et al., 2015; Rodríguez & Palacios, 2007).

The role of gesture in cognitive processing can be studied from many perspectives. This article specifically focuses on the role of gesture in enhancing executive functions. Executive functions are a family of top-down mental processes that are used when employing automatic processing or relying on intuition would be insufficient to do a cognitive task (Burgess & Simons, 2005; Espy, 2004; Miller & Cohen, 2001). It is commonly believed that executive functions consist of three skills (e.g., Cragg & Gilmore, 2014; Diamond, 2013; Lehto et al., 2003; Miyake et al., 2000): inhibition (the ability to suppress distracting information and responses), working memory: (the ability to monitor and manipulate information), and cognitive flexibility (the ability to shift between tasks and to change perspectives flexibly). Inhibition enables us to focus on what we choose to attend to (relevant information) and suppress what interferes (irrelevant information or stimuli). We can choose to inhibit attending to particular stimuli or information and attend to other stimuli or information based on our goal or intention (Diamond, 2013). Inhibition has been termed top-down, active, or executive attention (Posner & DiGirolamo, 1998; Theeuwes, 2010). Our working memory enables us to hold information in mind and mentally working with it for a short period of time in the perceptual absence of that information (Baddeley & Hitch, 1994; Smith & Jonides, 1999). According to Diamond (2013), inhibition and working memory are closely interrelated, as focusing on information held in mind for a short period of time is closely related to keeping attention focused on those mental contents for that period of time. Cognitive flexibility, as the third component of executive functions, builds on inhibition and working memory (Davidson et al., 2006; Garon et al., 2008).

In this article, we discuss some evidence that suggests gestures can enhance executive functions during processing mathematical concepts. The role of gestures in enhancing executive functions is a key part of self-regulatory function of gestures. The effectiveness of gestures in improving the three components of executive functions are discussed separately. This will be done by a specific focus on the role of gestures in understanding mathematical concepts and ideas. Before that, the following section briefly looks at gestures and the ways through which they contribute to cognitive processes.

The role of gesture in cognitive processes

Gestures are body movements that are used to talk or to think about an idea or meaning. Gestures are often intentional behaviors that may or may not be accompanied by speech. They emerge in early infancy. Children produce gestures much earlier than they can talk (Bates et al., 1989; Cavalcante et al., 2019; Camaioni et al., 1997; Cameron-Faulkner et al., 2021; Rodríguez & Moreno-Llanos, 2020; Volterra et al., 2018). Gestures present a visually perceivable representation of a concept or relations between concepts in the three-dimensional space. This visually perceivable representation may be iconic or metaphoric. Iconic body movements directly show the shape of an object through the trajectory of body movements. For example, we may use the trace of hand movements to talk about a sphere. Metaphoric body movements or body states refer to metaphorical meanings of concepts (McNeill, 2005). Metaphoric body movements and body states are often used to describe abstract concepts.

Among the mediatory tools that are used to facilitate thought processes, gestures have been the focus of many studies (e.g., Johnson-Glenberg & Megowan-Romanowicz, 2017; Macedonia, 2019; Yeo, Ledesma, Nathan, Alibali, & Breckinridge Church, 2017; Radford, 2003). Mathematics teachers use gestures to present a visually perceivable representation of mathematical concepts and problems they are talking about (e.g., Alibali & Nathan, 2007; Flevares & Perry, 2001; Goldin-Meadow et al., 1999; Nathan & Walkington, 2017; Richland et al., 2007). These gestures could be representational (iconic or metaphoric), ostensive (gestures that are used when the hand holds an object), or indexical. Students employ gestures to talk about newly learned material even before they express it through speech (e.g., Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Perry et al., 1988). It has been suggested that gestures have a prominent and maybe a causal role in the process of acquiring new knowledge (e.g., Alibali & Kita, 2010; Khatin-Zadeh, 2021; Radford, 2009; Singer et al., 2008).

Using gestures when we talk or think about concepts suggests that some aspects of knowledge are embodied (Gibbs, 2006; Hostetter & Alibali, 2008; McNeill, 2005; Núñez, 2005). Embodied knowledge means that the process of knowledge acquisition is supported by sensory, perception, and motor systems (Glenberg, 2010). Gestures contribute to and facilitate the process of thinking by focusing attention on perceptual information (Alibali & Kita, 2010), by organizing ideas and thought processes (Kita, 2000; Kita & Davies, 2009), and by activating and maintaining mental images (Wesp et al., 2001). Gestures can enhance mathematical thinking by reducing the load of working memory and organizing thought processes (e.g., Alibali & DiRusso, 1999; Goldin-Meadow & Wagner, 2005; Wagner et al., 2004). Alibali and Nathan (2012) argue that gesture contribute to mathematical thinking by externalizing information and grounding them in the physical environment. In fact, gestures can reduce the load of processing by transferring some parts of the load of cognitive processing into the environment (Kirsh & Maglio, 1994). The following section discusses the role of gesture in inhibition as the first component of executive functions.

Contribution of gesture to inhibition

The mechanism of inhibition may play a key role in doing some cognitive tasks, particularly when the individual needs to focus on a specific part of information or stimuli. If inhibition is not done properly, the interference of unnecessary information or stimuli will disrupt the process of understanding. Here, the necessary or relevant information should be kept at the focus of attention while the unnecessary, irrelevant, or extraneous information should be suppressed. How can gestures contribute to this suppressive process during understanding a mathematical concept or idea? As mentioned, we may use iconic or metaphoric gestures to present a concrete or visually perceivable representation of a concept. In the case of iconic gestures, the shape and movements of body parts directly reflect the shape of an object. This kind of gesturing is very common in mathematics discussion. In the case of metaphoric gestures, the shape and movements of body parts present a visual representation of the base concept through which the target concept is understood. For example, the mathematical concept of limit is metaphorically understood in terms of movements of points on a line (Khatin-Zadeh et al., 2021; Lakoff & Núñez, 2001; Marghetis & Núñez, 2013; Núñez & Lakoff, 1998).

Both iconic and metaphoric gestures can contribute to the process of inhibition. In both cases, that part of information or that part of representation that needs to be focused on can clearly be highlighted by gestures. In other words, the most important and the most relevant information is highlighted and kept at the focus of attention by gestures, while the irrelevant information, which plays no role in the processing of the concept in that specific context, is disregarded. Two examples may help us make the point clearer. An algebraic function can be represented by a graphical representation in the Cartesian coordinate system. The graphical representation visually shows some features of the function that may be very difficult to grasp through the algebraic representation. The graphical representation clearly shows where the function is ascending, where it is descending, where it is concave upward, where it is concave downward, and many other features. When we want to focus our attention on the concavity of a function, gestures can be helpful. Shape and movement of hands can visually show what concavity means. In this case, those features of function that are irrelevant to concavity (e.g., having a positive or negative value) are disregarded. The second example is limit. The concept of limit is metaphorically understood as a motion event. When it is said that $\lim_{x \to c} f(x) = L$, it means that as x approaches c, $f(x)$ approaches L. In fact, the distance between $f(x)$ and L can become smaller than any small distance as x approaches c. In this metaphorical description, the most relevant information concerns the dynamic distance between x and c as well as the distance between $f(x)$ and L. Other parts of information are irrelevant. Here, it is not relevant whether c and L are positive or negative values; it is not relevant whether c is a natural number, an integer, a rational number, or an irrational number. These are irrelevant to general definition of limit. In such cases, gestures can be used to focus attention on those parts of information that are relevant to the general definition of limit. Here, the important information is the dynamic distance between x and c, the dynamic distance between $f(x)$ and L, and also the way that the distance between $f(x)$ and L is dependent on the distance between x and c. Gestures can be used to focus attention on these dynamic distances. In this way, those parts of information that are irrelevant to the general definition of limit are kept out of focus of attention.

Since many fundamental concepts in mathematics such as limit, derivative, integral, continuity, and function can metaphorically be described in terms of motions, gestures can play an effective role in their understanding. Motions are inherently dynamic phenomena. Understanding such phenomena involves focusing on several interacting elements at the same time, which makes their processing difficult. The interference of irrelevant information could make their processing even more difficult. Therefore, the inhibitive function of gestures can be very helpful in the processing of mathematical concepts. The following section discusses the role of gesture in enhancing working memory as the second component of executive functions.

Contribution of gesture to working memory

The way we remember words may be different from the way we remember actions (Cook et al., 2010). The contribution of gestures to memory has been demonstrated in several studies (e.g., Cohen, 1981; Cook & Fenn, 2017). Wesp et al. (2001) found that co-speech gestures help us maintain spatial representation in our working memory. Results of an experiment conducted by Morsella and Krauss (2004) indicated that gestures can directly enhance both spatial working memory and speech. Cook et al. (2012) specifically investigated the impact of gestures and meaningless body movements on working memory during explaining mathematical ideas. They found that gestures can reduce the load on working memory when people talk about mathematical ideas. Three related studies reported that when people were asked to explain their solutions to a mathematics problem, they remembered more items when they were allowed to gesture than when they were not allowed (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Ping & Goldin-Meadow, 2010; Wagner, Nusbaum, & Goldin-Meadow, 2004). A question raised here is how gestures can support working memory during the processing of mathematical concepts and ideas. Two possible answers are discussed here. One answer is based on Ravizza's (2003) hypothesis, according to which gestures can facilitate speech production by prompting neural activities in motor areas that are involved in speech production. From this perspective, gestures facilitate speech production by increasing activities in motor areas that are responsible for speech production. Therefore, gestures enhance learners' performance when they are asked to recall and explain the mathematical ideas they have learned. This may partly explain how gestures can enhance working memory when we talk about mathematical concepts. Although this may be interpreted as the role of gestures in improving working memory, it is in fact the enhancement of speech production not working memory.

Another possible answer is based on the nature of metaphors that are used to describe mathematical concepts and the role of the motor system in understanding such metaphors. As mentioned, many fundamental mathematical concepts are metaphorically described in terms of movements. From the perspective of the strong versions of embodiment (Gallese & Lakoff, 2005), processing these metaphors could involve the activation of the motor system, as the base concepts of these metaphors are motion events. This is particularly the case when gestures are used to describe base concepts of mathematical metaphors. Therefore, gestures can play a contributory role in the processing of those mathematical concepts that are metaphorically described in terms of motion events, as they increase activity in the motor system. From this perspective, gestures are directly involved in the processing of mathematical concepts. This may explain why gestures can enhance working memory during mathematical processing. Furthermore, when gestures are used to present a metaphorical description of a mathematical concept, they help us maintain a visual (embodied) representation of those parts of information that are difficult for us to keep in our working memory. In fact, gestures can help as an external storage that keeps some parts of information for a short period of time in order to manipulate that information or to combine it with other information in later stages of processing. Therefore, gestures can be seen as an external working memory. When a large volume of information has to be processed during a short period of time, gestures can take the responsibility of keeping some parts of information. In this way, they reduce the load and allow us to use the freed cognitive resources in dealing with other parts of information. In fact, gestures can play a dual-role. In addition to keeping some parts of information in a visual format for a short period of time, they allow the freed resources to be used to focus on other parts of a task. The following section discusses the role of gestures in enhancing cognitive flexibility as the third component of executive functions.

Contribution of gesture to cognitive flexibility

According to Diamond (2013), cognitive flexibility has three dimensions: shifting between spatial perspectives and between personal perspectives flexibly, changing the way that we think about something, and adjusting to changed demands and priorities flexibly to address or to take advantage of new conditions. She adds that cognitive flexibility is dependent on the first two components of executive functions. Therefore, gestures can enhance cognitive flexibility indirectly through enhancing the first two components of executive functions. However, gestures can contribute to cognitive flexibility in some other ways as well. Describing a mathematical concept or idea in terms of gestures enables us to have a spatial representation of that concept or idea. This representation can be processed from a variety of spatial perspectives. For example, the algebraic representation of a function can be described by a graphical representation in a Cartesian coordinate system. This graphical representation can be shown by body gestures in the three-dimensional space. The graphical representation can be viewed from a variety of spatial perspectives. Also, in geometry, many shapes can be described through gestures. The gestural representations allow us to flexibly shift between a variety of perspectives. This function of gesture can even be helpful in interpersonal communication, which is one dimension of cognitive flexibility. Gestures can be used by both sides of a conversation. Therefore, they can help interlocutors shift spatial perspectives during the process of communication.

Conclusions

The aim of this article was to argue that gestures enhance the three central components of executive functions for the understanding of mathematical concepts. It was proposed that gestures can enhance the three components of executive functions in a variety of ways. Gestures can be used to focus our attention on the most relevant parts of information by highlighting these parts of information. Other parts of information, which are irrelevant to the cognitive task, are disregarded and thus are suppressed. In this way, gestures contribute to inhibition. The contribution of gestures to working memory was explained on the basis of metaphors that are used to describe mathematical concepts in terms of motion events. Gestures increase activity in the motor areas of the brain. In this way, they may facilitate the process of understanding those abstract concepts that are metaphorically described in terms of motion events. Also, gestures can keep some parts of information for a short period of time in order to manipulate that information or to combine it with other information in later stages. When a large volume of information has to be processed during a short period of time, gestures can maintain some parts of information in a visual format. In this way, they reduce the load on our cognitive system. The freed resources can be used to tackle other parts of the cognitive task. Since cognitive flexibility builds on the first two components of executive functions, gestures can contribute to it through enhancing the first two components. Furthermore, describing a mathematical concept or idea in terms of gestures enables us to have a spatial representation of that concept or idea for a period of time. During this time, we can shift our perspective and process that concept or idea from a variety of perspectives.

Finally, it should be noted that in this paper we focused on the role of the three classical components of executive functions. But, other components of executive functions such as planning and monitoring may also be supported by gestures during processing mathematical concepts and relations. This is particularly the case with highly complex mathematical concepts and relations whose understanding may involve combining a large set of interrelated elements. In such cases, in order to acquire a clear understanding of concepts and relations, the individual may need to plan for organizing information and monitor the process of planning. Here, gestures can be a contributing tool for keeping each element and information related to it in the right place in the physical environment or in the mental space of the individual. A detailed description of the role of gestures in enhancing non-classical components of executive functions is a question that can be addressed in future studies.

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Declarations

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