Gestures Can Create Models that Help Thinking

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ABSTRACT

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People gesture every day and everywhere. They gesture in communication, speech, and for themselves while thinking. A large number of studies have explored the gestures in speech and communication under a variety of conditions. However, gestures for thinking did not draw much attention, yet they are natural and spontaneous behaviors of the human being and can reveal the way people process information. Gestures in thinking are also believed to be beneficial in comprehension and memory. Previous studies have demonstrated that people gesture for spatial thinking tasks such as map reading and text navigation test. Theories on embodied cognition and grounded cognition claim that gestures are needed when people visualize the models in mind. What if the models are not inherently spatial? Will people gesture for abstract information? Or on the contrary, what if the models are already presented in visual spatial form that you can simply copy the image, not build one on your own? Will people gesture for diagrams and maps? If so, what kind of gestures will they use? Will gesture improve comprehension and memory?

This work provides evidence that people gesture for not inherently spatial models and spatial models that are presented in diagrammatic format. For information that is not inherently spatial, participants use representational gestures to facilitate the visualization. For instance, a temporal schedule can be visualized into a two-dimension table. For linear order text, people create a list of items that are organized by a certain order. When the spatial and not inherently spatial models are presented in maps or diagrams, representational gestures were still observed and beneficial for the memory test.
Due to the limited sample size and other limitations of the lab setting experiment, these studies did not provide strong results that support the hypotheses that gestures help people comprehend and memorize information. Gestures were found beneficial for only one type of stimuli (mechanical systems) and an overall effect on memory test scores across text and diagram stimuli. Even though the effect of gestures was not significant between different types and formats of stimuli, it was in the right direction. Future research with more sensitive measurements could further explore gestures for thinking.
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CHAPTER I INTRODUCTION

Rationale & Research Questions

Human beings use their whole body to express themselves, in spoken and non-spoken ways, to others and to self. Hand gesture is one of the most common non-spoken way and people use it every day in all kinds of contexts. The studies in this dissertation investigated the scenarios in which people gesture for self, the nature and pattern of the gestures, and whether gesture will facilitate comprehension and memory. In the previous study gesturing was found beneficial for learning spatial models that describe environments. It was natural and intuitive to use gestures on such occasions since gesture is a spatial form of embodiment and represent spatial relationships. People who gestured in the study achieved higher score in the memory test. However, spatial models only make a small part of our life. Abstract concepts are used in many occasions. Therefore, the next step of exploring the spontaneous gesture was to examine the gestures that were produced for non-spatial models. The models used in Study 1 described abstract concepts such as linear order, temporal schedules, and the structure and function of the mechanical systems. These models were not inherently spatial but can be spatialized. The information can be organized in a spatial way, such as a list for the linear order description and a two dimensional table for the schedule. Study 1 discussed whether or not people would gesture for such models. And if so, what would the nature of the gestures be? And most importantly, will gestures improve comprehension and memory?

In previous studies and Study 1, the stimuli were all presented in text. It was assumed that gestures were used to ground the information and translate the text into visual spatial representation. If people need hand gestures to help them process and visualize the models presented in text, would they gesture for stimuli that were already in visual spatial form? Study 2
explored whether or not participants would gesture for diagrams. What would the gestures look like? And again, whether these gestures could improve the performance in the memory test following each stimulus? In this study, both inherently and not inherently spatial models were used and they were presented in both text and diagram forms.

**Dissertation Overview**

In the following chapters, Chapter II provides a brief review of the literatures on gesture and the fundamental theories of gestures in learning. Chapter III reports the design and results of study 1. This study was conducted with research colleague, Melissa Zrada. Chapter IV describes study 2, which is an independent research of the author.
CHAPTER II LITERATURE REVIEW

This review is organized into three parts. Part I is a review of theories of embodied cognition and grounded cognition. Part II explores the benefits of gestures for others and for self in various situations. Part III compares gesture and diagram to in visualizing actions.

Embodiment and Grounded Cognition

The traditional theory of cognition assumed that our brain processed concepts through the amodal symbols. This perspective left all responsibility of cognition to the brain, ignoring the participation of the body and the interaction between our body and the environment. Instead, grounded cognition theories suggest that actions and bodily state are the undeniable part of our cognition. To develop a full understanding of a concept we need to create a modal representation of it (Barsalou, 2008).

Cognition is grounded and embodied. It was believed that our knowledge represents the world with amodal, abstract, and arbitrary (AAA) symbols for semantic knowledge (Glenberg, Gutierrez, Levin, Japuntich, & Kaschak, 2004). The AAA symbols code meanings of concepts. However, the major problem of this theory is that the meanings of the concept are not grounded, namely, the symbols are not connected with perceptual input and actions (Glenberg & Robertson, 2000). Therefore, it is difficult, even impossible, for people to understand a foreign language only from the amodal and abstract symbols. One cannot explain a symbol using a set of symbols without grounding any of them to visual or spatial experience that can be understand universally (Seale, 1980). The embodied nature of our mind makes it possible for us to learn and reason, to store and retreat information, to make connections to various experience (Lakoff & Johnson, 1999). If the AAA symbols don't generate meaning by themselves, grounding the meanings to perceptual experiences and actions is essential.
Modal representation is fundamental in human cognition. An increasing body of studies has shown that human cognition uses modal representation for comprehension and memory. The question to the inadequacy of the traditional perspective of cognition was first raised in linguistic field (Lakoff & Johnson, 1999; Gibbs, 2005). Soon the debate spread to philosophy, computer science, cognitive science, artificial intelligence, and neurology (Barsalou, 1999; Decety & Grezes, 2006; Goldman, 2006; Pecher & Zwaan, 2005). Although taking a different perspective, these studies demonstrated that modal representations are essential to cognition. Bodily experiences are the main source of our knowledge to the world. The simulations from the real world form our knowledge in a multimodal way and store in our mind as concepts. Therefore, no matter the concept is mentioned in any aspect, we can always retrieve the whole picture of the concept. For instance, one ate a cake. Later this person could recognize the cake by its name, shape, color, taste, smell, texture, or anything related to this particular cake (Barsalou, 2008).

The agreement on the importance of modal representations leads to studies on simulation mechanism. And evidence from neuroimaging showed that even small mental images can activate visual cortex and the brain area that used in vision is also active when constructing visual mental imagery (Kosslyn, 1994; Kosslyn et al, 1993). Mirror neurons, first discovered by Rizzolatti and colleagues in monkey’s brain (Rizzolatti et al.,1996), were activated not only when an action is produced, but also when the action is perceived. It seems that we automatically simulate other’s perception and action in our own mind to understand their mind. Simulation is the way we interact with the world. This is strong evidence that cognition is grounded in simulation, situated actions, or sometimes bodily state.

There are many approaches of grounded cognition. Cognitive linguistic theories are partially the origins of grounded cognition that emphasize the situations, simulations, and the
relation between the body and the environment. Researches have shown that the metaphors are not only a linguistic tool but also play an important role in our thoughts and shape our cognitive mechanism (Gibbs, 2006; Slepian & Ambady, 2014). When the object is concrete such as a building or a tool, we describe it as it is. But when we try to understand and convey communication upon an abstract concept, we do it metaphorically. The metaphors being used are based on the embodied and situated knowledge of everyday life (Lakoff & Johnson, 1980). For example, the phrase “cheer up” includes a hidden assumption that mood can have directions in which good is up and bad is down. The mental illness, bipolar disorder, is diagnosed when the patient’s mood or emotions switch between periods of elevated mood and severe depression like the two poles of the earth, both extreme and far away from each other.

**Action plays central roles in cognition.** Theories of situated action are another main approach of grounded cognition. These theories emphasize the role of the environment, and explore the close relation between action and perception in goal achieving activities (Prinz, 1997). Behavioral researches and neurological evidence have confirmed that perception and action can play central roles in human cognition.

Action and perception affect each other mutually. The literature about the relationships between perception and action shows three interaction models between the two. First, perception is for future action and the following interaction with the environment (Gibson, 1979; Adolph, 2000). In Prinz's (1997) model of the relationship between perception and action, perception and action share common codes in the brain. Perception leads to the planning of the actions. A perceptual event triggers stimulation in the sensory system and sends signals to the brain where the sensory code is translated into motor code before a reaction is evaluated and taken. Second, action reflects perception. Tversky (2011) proposes that the actions of people organizing things
into categories are the embodiment of the Gestalt laws of perceptual organization. Memories of the perceptual experience can serve as a guide of the action. When a familiar situation is presented and the memory is triggered, the perception experience will be used to evaluate the feasibility of future action (Glenberg, 1979). Last but not least, action can influence perception and cognition. A study on infant cognitive development explored how action experience changes the perception of other's action (Sommerville, Woodward, & Needham, 2005). The researchers found that action experience facilitated action perception. The infants who perform the reaching action focused on the relation between the performer and their goal when watching a similar action, but the infants who only watched the action did not. The action had a positive effect on the infant to develop goal-based perception.

According to theories of mirror neurons, the corresponding areas of our brain can be activated when an action is perceived by construct simulation in our mind. However, a movement can be triggered only when the activation crosses the threshold from premotor cortex to motor cortex. Hostetter and Alibali (2008) introduced the gesture-as-simulated-action (GSA) framework that explains how gestures are produced from the language. There are three steps. First the language and mental imagery (both visual and motor imagery) influent each other. Then the mental images interact with the perception-action circle in both directions. The perception-action circle serves as a simulation to activate the neural areas in our brain that involve the action or planning the action. When the activation is strong enough to spread from premotor cortex to motor cortex, a gesture is produced. However, this framework only explains how a gesture is produced but doesn’t discuss how the gestures will influence language processing and mental imagery. Even though this study focused on gestures in speeches, from the moment the gesture is
produced, it becomes a new input of the mental imagery, both as visual and motor image, and should be included in the new iteration of gesture production.

The action compatibility effect is another demonstration that one’s bodily state and mental state are related. Again there is evidence in cognitive linguistic research shows that it is easier for the participants to act when the action and the sentence is in the same direction. The famous drawer experiment conducted by Glenberg and Kaschak (2002) found that asking the participants to make a moving-away action when the sentence is “close the drawer” is easier to make a sensible judgment because usually closing a drawer means pushing the drawer away. Wilson and Gibbs (2007) have demonstrated in their experiments that perceiving or imagining compatible body movements facilitate comprehension of the metaphorical expressions (e.g., shake off a feeling, grasp a concept) even when the sentences are not describing physical movement.

**Gestures as a Form of Embodiment Promotes Comprehension and Memory**

As the most functional part of our body, we use our hands excessively and make hand gestures on various situations across cultures (Feyereisen & De Lannoy, 1991). Even those who are born blind gesture (Iverson & Goldin-Meadow, 1998a). Gesture is an important form of embodiment and a growing body of researches has shown that gesture promotes cognition and learning in various domains such as mathematics, second language learning, problem solving, and spatial cognition.

**Gestures in cognitive activities.** Studies that explore the positive effect of gestures on cognitive activities focus on how the gestures can facilitate information delivery and retrieve, especially in educational settings.
Co-speech gestures may be the most common gesture type that we can see every day. This kind of gesture is widely examined in a variety of situations. Although speech is a communicative activity, the co-speech gestures can benefit both the speaker and the listener in communication and comprehension (Iverson & Goldin-Meadow, 1998b). The Gesture as Simulated Action (GSA) framework (Hostetter & Alibali, 2008) suggests that gesture facilitates thinking with mental images in the specific situation. The lexical access hypothesis (Krauss, Chen, & Gotfexnum, 2000) assumes that gestures are helpful in lexical items retrieval for spatial and motor concepts. People gesture more when describing visual items from memory and when the object is difficult to depict verbally (Morsella & Krauss, 2004). When gestures are prohibited, speech becomes influent (Hostetter, Alibali, & Kita, 2007). This suggests that gesture has also involved the formation of speech and help people organize spatial information that can be delivered verbally. This study also found that people tend to gesture more when a visual item is difficult to conceptualize. McNeill (2005) proposed the growth points theory that verbal and non-verbal data are tangled together to form speech and ideas. A growth point is the combination of linguistic and imagistic components. Gestures, in this case, are the non-verbal data.

Neurological evidence proved that gesture and speech interact in comprehension (Holle, Gunter, Ruschemeyer, Hennenlotter, & Iacoboni, 2008) Dick, Goldin-Meadow, Hasson, Skipper, & Small (2010) used fMRI to examine how co-speech gestures affect the activation regions in the human brain. The participants watched three audiovisual stories in which one has matching co-speech gestures, one shows unrelated hand gesture, and one with no gestures. The researchers found that the right inferior frontal gyrus shows a stronger reaction when the gesture is semantically unrelated to the speech, indicating the listeners try to find meaning from the gestures.
Gesture promotes mathematical problem-solving. Numerous studies have found that gestures are useful in mathematics education. The conductor of the gesture can be either the instructor or the student. Cook, Mitchell, and Goldin-Meadow (2008) found that children will find it easier to retain the knowledge if they gesture during the learning process. They encouraged children to use gesture strategy when solving mathematical equivalence problems. Compared with those who received speech only instruction of the same strategy, children who used gestures achieved higher scores. Jamalian (2014) used grouping gestures amongst preschoolers in a counting task. The results show that children that applied the grouping gestures significantly outperformed the control group. The author argued that the gestures add a layer of meaning with action over the visual input of information, thus promote learning directly. Earlier research (Goldin-Meadow, Kim, & Singer, 1999) also showed that perceiving compatible gestures along speech can reinforce understanding and memory and watching mismatched gestures will produce an opposite effect. Although the beneficial effect of gesture has been widely accepted, it is not clear whether the movements on other body parts also involved. Cook, Friedman, Duggan, Cui, and Popescu (2015) developed an animated pedagogical agent to replace the real human teacher in the mathematical equivalence task. The authors controlled facial expression and body movements of the avatar so that gesture is the only factor that differentiates the experiment group and the control group. Children in the gesture group learned more and solved problems with less time than those who didn’t see gestures.

Gesturing is also beneficial in spatial problem-solving. Chu & Kita (2011) demonstrated that co-thought gestures improve performance in spatial visualization tasks. Participants were asked to finish the mental rotation tasks and the paper folding tasks. People who spontaneously gestured significantly outperformed those who didn’t. This finding is consistent with former
researches on using gesture in mental rotation tasks (Schwartz & Black, 1996; Wexler, Kosslyn, & Berthoz, 1998; Wohlschläger & Wohlschläger, 1998). Ehrlich, Levine, and Goldin-Meadow (2006) explored the sex difference in spatial skill between 5-year-old boys and girls using spatial transformation tasks. Both boys and girls’ performance improve after a brief training. Boys showed significantly better spatial skills in both pretest and posttest. Children who used more gestures when explaining their problem-solving strategies also showed better performance on the task. However, this study did not provide evidence that gesture is the only or main reason for the superior performance in spatial reasoning due to the lack of control on other factors. In a navigation task conducted by Jamalian, Giardino, and Tversky (2013), participants were asked to learn and remember descriptions of space from either route or survey perspective and then answer true/false questions derived from each description. The results show that people who spontaneously gestured at study or at test did considerably better in the memory test.

Gesture promotes reasoning. Again, the effect of gesture can work to both the performer and the observer end. Beaudoin-Ryan and Goldin-Meadow (2014) investigated how gestures can help in moral development. They asked fifth graders to solve three moral dilemmas with gesture manipulation in one of the moral problems and count the proportion of responses that containing multiple perspectives. Students who gestured under instruction or spontaneously produced more multiple perspectives responses than those who were asked not to move their hands when explaining their solutions. Thus, this study demonstrated that gestures augmented moral reasoning. Sassenberg, Foth, Wartenburger, and van der Meer (2011) discussed the relationship between gesture production and reasoning skills through geometric analogy task. They used fluid intelligence and crystallized intelligence as indices for reasoning ability. The participants were assigned to four conditions based on their score in the pretest of the two intelligence tests. They
were asked to explain their strategies in the geometric analogy tasks and their gestures were coded. The results showed that gestures production is positively correlated with fluid intelligence.

Gestures facilitate social interaction. When interacting with others, language is not the only vehicle of our intentions. We also use gestures and facial expressions to deliver spatial information, emotion, and other non-verbal content. Think about how easy it is to make misunderstandings when communicating via phone call or text message. Reading other’s gesture complement the interaction. Goldin-Meadow, Wein, and Chang (1992) recruited untrained adults to assess children’s reasoning ability. The adults were asked to watch short videos of children explaining their judgment on some phenomenon (e.g., refraction of light) and then evaluate the reasoning and knowledge level of the children. The adults showed more uncertainty in the evaluation when children’s speech and their gestures are mismatched than when the speech and gestures were conveying the same meaning, indicating that the adults spontaneously read children’s gestures to understand and evaluate. In the more general social interaction situations, do we naturally interpret other’s intention through their gestures? With a series of experiments that controlled gaze direction and request gesture, the researchers discovered that, even without speech, direct gaze or request gesture to communicate can affect the reaction of another individual (Innocenti, De Stefani, Bernardi, Campione, & Gentilucci, 2012). Neuroimaging evidence also shows that gesture and body-orientation are related to the feeling of being addressed in face-to-face communication. Perceiving gestures from another individual active the brain regions that involve in motor simulation, empathy, and mentalizing (Nagels, Kircher, Steines, & Straube, 2015).
**Gestures help lighten cognition load.** We have discussed the situations that gestures can be beneficial in comprehension and memory. In this part, we review how gestures help in thinking and what features are shared by various tasks in empirical evidence.

To explore how gestures help people learn, researches have looked into the teaching and learning process such as maths, second language learning, and spatial problem solving, to name a few (Goldin-Meadow et al, 2001; Cook, Mitchell & Goldin-Meadow, 2008; Cook, Yip & Goldin-Meadow, 2012; Chu & Kita, 2011; Tellier, 2005). However, although these researches provided empirical evidence to show that gestures can help with comprehension and memory in thinking, speaking, and problem solving, they can only suggest assumptions of how people benefit from the gestures. Solid evidence from behavioral and neurology is sparse.

One of the most accepted assumptions of how gestures improve the performance in math and memory believes that gestures lighten the load of working memory. In the study of solving math problems and then doing memory tasks, Goldin-Meadow and colleagues (2001) found that with the help of gestures, both children and adults have better performance in memorizing a long list of words or letters. The benefit didn’t show in the short list task. The limitation of this study is the ceiling effect in the short list task, especially for the adult group when the scores are already quite high without gesture instructions. Ten years later, a follow-up study (Cook et al., 2012) was conducted with three conditions in which participants were instructed to use meaningful gestures, meaningless gestures, and no gesture while explaining the solution of the math problems. A list of letters was used as a memory test as in the previous study. The results show that the participants doing meaningful gestures performed significantly better in the memory test. In the study of second language learning by Tellier (2005), students who gestured
while repeating the words achieved a significantly higher score in words memorization test than their peers who didn’t gesture.

There are three assumptions of how the working memory load is lightened by the gesture. First, gestures help increase cognitive capacity by conveying lexical information in a more intuitive way. The visuospatial representation works as a second modality to encode the same information and makes the abstract concepts concrete and perceptible (Singer, 2017). The co-thought or co-speech gestures split the burden of working memory by directing the load to another format of the information. Second, unlike meaningless gestures that can be considered as a distraction, meaningful gestures help the participant keep concentrate. In this case, the gesture is both a production of the thoughts and an input of the mental representation. Last but not least, evidence in cognitive neuroscience have confirmed that verbal and visual input were processed and stored in different parts of the human brain. Therefore, it’s possible that gestures help shift the workload from verbal to spatial so that release the resources in working memory to better serve the verbal information in the memory tasks.

Unlike the lexical input mentioned in the studies above, gestures directly facilitate spatial problem solving. In a mental rotation task, participants benefit from gestures when the problems become difficult. Researchers argued that gestures externalize the mental representation to help lighten the spatial working memory and facilitate the internal computation of spatial transformations (Chu & Kita, 2011; Jamalian et al., 2013). Tversky and Kessell (2014) found in their study of comparing diagram and gestures that when “translate” language to mental representations, gestures can help people abstract the problem, eliminate irrelevant information, thus lightened the cognitive load.
In this part, we discussed the effect of gesture on cognitive activities in various situations, and the mechanism of the benefit of gesture in cognition. In the following part, we will review diagrams, as a form of information visualization, is widely applied in and out of the educational settings. Diagram shares many similarities with gesture yet work differently on human cognition. 

**Compare Gesture and Diagram**

Diagrams, as a widely used form of information visualization, also have benefits in reducing cognitive load and promote learning. In this section, we will review the using of diagrammatic representations in different situations and discuss theoretical and empirical evidence from previous studies. At last, we will compare the two visualization tools, gesture and diagram, and reveal their similarities and differences in cognitive activities.

**Diagrams in cognitive activities.** Diagrams promote learning in math and science. In a study about the effect of self-explaining strategy, Ainsworth and Loizou (2003) used two formats of the learning material, text and diagrams. Twenty participants were randomly assigned to each condition and learned the human circulatory system in either text or the diagrams that adapted from the text. Participants were given pre-tests and post-tests. The results showed that students who were given diagrams outperformed those who were given text materials on test scores. The diagram group produced more goal-driven explanations and participants who produced more self-explanations achieved higher scores in the post-test. For spaced restudy of the 10th grade biology, diagram-based materials exceeded text-based materials on the effect on learning. Bergey, Cromley, Kirchgessner, and Newcombe (2015) conducted this study amongst tenth graders in the real classroom setting. Students were randomly assigned to either diagram-based restudy(DBR) condition or traditional text-based restudy(TBR) condition during the warm-up stage at the beginning of class meetings. After the four-week intervention, the researchers found
that practice with diagrams leads to better diagram comprehension and progress on biology knowledge. A study among college students using conventions of diagrams found that people who learned from diagrams gained more progress on diagrammatic reasoning and a better understanding of the science material (Miller, Cromley, & Newcombe, 2016). For students who have learning problems, diagrams can be a good strategy to help them understand math problems. Xin, Jitendra, and Deatline-Buchman (2005) experimented the schema-based instruction in math for middle school students with learning problems. The schema-based instruction uses a schema diagram to represent the problem so that students could understand and transfer the problem into mathematical sentences to solve. Results showed that students in the schema-based group outperformed the general strategy instruction group in both immediate and delayed posttest.

Reading and generating diagrams are helpful in design and communication. In architecture design, architects use diagrams for symbols and concepts, and sketch for spatial form. Diagrams can represent relationships of shapes and items by omitting the pictorial details. Diagram is the tool for architects to communicate with others. (Do & Gross, 2001). Diagrams also play a central role in information system development. Good diagrams are bridges between the designer and the user (Moody, 2007). The purpose of the information system development diagrams is communication and good diagram design should follow the natural cognitive pattern of human graphical information processing. Good diagrams and diagrammatic reasoning are especially important when the content is highly professional. Brunstein, Brunstein, and Marzuk (2015) introduced well-designed diagrams in medical risk communication. The results showed that diagrams compensate the missing medical knowledge of non-medical students and help
them to understand the medical risk better. This is a result that can be adopted by doctors when explaining medical risk to patients and support the patients in decision making.

**Mechanism of diagrams in cognitive activities.** Diagrams promote comprehension and memory in cognition and learning. Theories about how diagrams can be helpful are as follows.

First of all, diagrams can reduce cognitive load. The theory of cognitive load claims that if the elements in the learning material are highly interacted, the intrinsic cognitive load will high, thus this material is difficult to learn (Sweller, 1994). Group of elements in the diagram must be encoded into chunk to reduce cognitive load (Kosslyn, 1989). Ainsworth and Loizou (2003) assumed that using two modalities when presenting information can lead to powerful learning, then combining text and diagrams will maximize memory resources. Diagrams in this condition worked as the organizer of information chunks.

Second, diagrams show causal explanations either within a single diagram or across multiple diagrams (Ainsworth & Loizou, 2003). Text explanations of complex systems need to be read and processed carefully for the relationships between parts and this process demands high cognitive load. A positive effect of tree diagrams was found on comprehension and memory in an early research. Guri-Rozenblit (1989) examine the effect of the tree diagram by comparing text comprehension and memory between groups of participants who were assigned into four groups, whether the text was accompanied by a tree diagram, and whether there was additional verbal explanation. She found that the performance was significantly better for diagram groups overall and even better for the group with diagram and accompanying additional explanation.

Grant and Spivey (2002) use eye-tracking technique to study the visual attention pattern of diagram-based problem solving. They found that people who focus on the structure of the
diagrams are better problem solvers. And reasoning is positively affected by the shifts in attention due to perceptual changes in the diagram.

**Comparing gestures and diagrams.** The roles and benefits of gesture has been reviewed in the last three sections. Gestures can facilitate communication, problem-solving, social interaction when the gestures are meant to be read by others. It can also help spatial cognition, reasoning, and speech producing when people gesture for themselves. Gestures and diagrams both convey meanings and structures. Compare to words, gestures and diagrams can present spatial or metaphorically spatial relations much more directly (Emmorey et al., 2000; Tversky, Jamalian, Giardino, Kang, & Kessell, 2013; Tversky & Kessell, 2014).

There are properties of the diagram that makes it unsubstitutable. First of all, diagrams are effective for constructing mental models because they can map out the relations between items in space and causalities in time utilizing lines, arrows, and blobs (Tversky, 2011; Tversky, et al., 2013). Second, the diagram has a nature of permanence. We can examine and re-examine the diagrams at any time as long as we keep them safe while gesture disappears by the moment the gesture ends (Kang et al., 2012; Tversky, Heiser, Lee, Daniel, 2009). And when presenting structures of complex systems, diagrams are ready to show the structure and relations of different parts while gestures can only depict parts of the system at one time (Kang et al., 2011). The third advantage of diagrams is that a good diagram can structure a problem with the most essential information and eliminate the irrelevant (Tversky, 2011). At last, a better diagram should also show the actions that should be taken with the parts, although it cannot really perform actions (Tversky et al., 2009).

No matter how excellent a diagram could be, it is a static 2-D image but we live in a three-dimension world. Processing information spatially is more natural to humans. Gestures,
however, add the dimension of action over diagrams and bring information alive. Unlike diagrams, not only can gestures model structures and relations visually, but also spatially (Tversky, et al., 2009). In the mechanical system explanation tasks, people who watched action gestures when learning the systems understood better on the function of the system than those who only watched iconic gestures. When explaining the system, people who watched actions depict more action gestures (Kang et al., 2011). Tversky and Kessell (2014) also found that participants rarely looked at their hands in the experiments. They argue that this is strong evidence that gestures create spatial and action representatives from which people can benefit more than visual ones.

Both diagrams and gestures have their advantages and disadvantages. To construct mental models, one form may be better than the other, thus it is wise to combine both for better understanding (Tversky et al., 2009). In the present study, we plan to demonstrate that to navigate in the environments and understanding mechanical systems, diagrams are not enough. We can use gestures as the additional modality to promote comprehension and memory.
CHAPTER III  STUDY 1
GESTURES FOR INFORMATION NOT INHERENTLY SPATIAL

Author Note

This study was co-conducted with Dr. Melissa Zrada, then doctoral student in Cognitive Science in Education at Teachers College, Columbia University. Dr. Zrada and the author contributed equally in this study.

Introduction

This study explored whether or not people would gesture for text descriptions that are not inherently spatial. Previous work showed that people spontaneously gesture when reading complex descriptions of space or solving simple or complex spatial problems and that their gestures modeled the situations described (Jamalian, Giardino, & Tversky, 2013; Tversky & Kessell, 2014). Here we ask whether people will spontaneously gesture when studying or solving a broader range of descriptions and problems. If so, what is the nature of the gestures; that is, do they represent the material and if so, how. Finally, we ask whether gesturing will improve inference, memory, and problem solving as for the spatial descriptions.

In this study, four kinds of texts and problems that were not inherently but could be spatialized were selected as stimuli. Participants read descriptions of linear orders (preference or economic growth), schedules (temporal relations), arithmetic (numerical relations) and mechanical systems (causal relations).

This study was expected to test three hypotheses. First of all the behavior of gesturing on not inherently spatial models needed to be confirmed. Then it was hypothesized that the gestures modeled the content. And at last, gesturing had a positive effect on learning and memory.
Methods

Participants. Participants were 125 Columbia University students, 18 years of age or older, paid or completing a course requirement. They were either native English speakers or attended an English-speaking high school.

Among the 125 participants, 103 were female and 22 were male, with an average age of 26 years old. (This average excludes 9 participants who incorrectly formatted their date of birth.) 66 participants (55%) reported that they were bilingual. The majority of participants (99) reported that their right hand was their dominant hand, followed by 10 individuals who were left-handed and 1 who was self-reported ambidextrous. Dominant hand data for 9 participants were not recorded. After the experiment, each participant completed a self-report of spatial thinking ability, ranging from 1 (poor) to 5 (excellent); the average reported score was 3.3.

Participants were assigned to one of two conditions: Gesture Prevented or Gesture Allowed. Researchers continued to recruit participants until at least 50 participants satisfied the criteria for each condition. This resulted in a total of 72 participants in the Gesture Prevented condition and 53 participants in the Gesture Allowed condition. Due to technical difficulties with the system that presented the stimuli and recorded the experiment, a total of six participants were excluded from analyses. One-third of participants in the Gesture Prevented condition used gesture at least once. Any participants in this condition who gestured were subsequently moved to a third group: Gesture Prevented but Observed. The final three groups and number of participants is as follows: 46 Gesture Prevented (GP), 50 Gesture Allowed (GA), and 23 Gesture Prevented but Observed (GPO).
**Materials.** Participants read six texts: two linear orders, two schedules, and two mechanical systems. After each text, participants were given true/false questions about what they had just read.

The linear orders were short, designed to be the easiest texts, and were followed by 6 true/false statements. Each text had four items with logical order (countries by economic growth and movies by preference).

The schedules were four sentences long, designed to be moderately difficult, and were followed by 16 true/false statements. Each schedule required participants to keep track of three activities, three times, and three people/celebrations.

The mechanical systems were designed to be the most difficult texts, and were followed by 16 true/false statements. Each mechanical system was comprised of two paragraphs, one a structural description and the other a functional description. Participants saw each description four times, in alternating order.

Besides the six descriptions, participants were asked to solve two arithmetic problems (numerical relations), one 3-digit plus 3-digit addition and one 2-digit by 2-digit multiplication. The two arithmetic problems were given as multiple choice questions with one correct and three alternative answers.

The three types of text description and the two arithmetic problems were presented in counterbalanced order. The true/false statements were presented in random order.

**Procedure.** Upon arrival, participants first signed the IRB Informed Consent and Participants Rights and agreed to be video and audio taped. They were then seated at a desk with a desktop computer and given brief instructions on how to advance the screen and answer true/false statements using voice control. Those assigned to the Gesture Prevented condition
were instructed to sit on their hands. The researcher began two recordings: one screen recording using QuickTime software to record participants’ response to questions and one video camera to record participants’ behavior during the study and test. Participants were left alone in the room for a practice trial.

Then the experimenter entered to answer any questions. Participants were then presented with the six texts. Participants studied the text description first in their own pace and then proceeded to the questions when they were ready. The questions were followed immediately after each description. When participants finished the test, a brief introduction passage for the next description will appear on the screen, leading the participants to the new description. There was no time limit for either the description or the test. The arithmetic problems completed the testing. This arithmetic task was added late so 10% did not complete it. Finally, participants completed a questionnaire that included the date of birth and several individual difference measures: bilingual status, hand dominance, and self-rating of spatial ability. Gesture Allowed participants were asked if they thought gestures aided understanding and memory, and what strategies they used to remember. Gesture Prevented participants were asked if they thought sitting on their hands affected their understanding and memory. All were asked to rate the difficulty of each text type.

SuperLab was used to run the experiment on an Apple iMac. Screen recordings were captured using QuickTime software. A video camera set up on a tripod to the right of the participant recorded the participants’ gestures.

**Results and Discussion**

**Participants.** Participants in the Gesture Allowed and Gesture Prevented conditions did not differ significantly on age ($t(87) = 0.050, p = 0.279$), bilingual ($t(94) = -0.780, p = 0.437$),
gender (t(93.288) = 1.082, p = 0.282), dominant hand (t(87) = -0.217, p = 0.829), and self-report spatial thinking ability (t(94) = -0.900, p = 0.370). Since there were 23 participants who were moved to the third condition (Gesture Prevented but Observed, GPO), the comparisons among all three groups were conducted and no significant differences were found on the variables above.

**Gestures coding.** Only the representational gestures were coded in this study. The representational gesture was defined as a set of gestures that represent the relations among the concepts described in the text. For most of the time, a representational gesture can be clearly differentiated from a beat gesture or fidgeting. The intentions of the gestures were also validated through an informal post interview. After the test, the experimenter showed the video to the participant and asked them to explain their gestures. For example, for linear orders, participants often arranged the movie genres or countries in order by pointing on the palms of their hands, making a list of the items. For the schedules descriptions, participants were observed arranging the events in the air, on their knuckles, or on the desk, making an invisible table of the schedules. For the mechanical systems, participants modeled the actions of the parts of the systems, for example, the flow of brake fluid down to the brake shoes and the action of the brake shoes on the wheels. There was considerable variability in the detailed ways gestures modeled, similar to variability in people’s diagrams of STEM systems (Bobek & Tversky, 2016; Kang & Tversky, 2016).

The variability of models for linear orders, schedules and mechanical systems suggests that participants were creating their own models, not using established ones. That was not the case for arithmetic, where most participants wrote the numbers in the air or on the table, a well-
practiced routine learned in school. Other movements, such as fidgeting, were not counted as gestures.

The location, hand use, symmetry, and looking at hands were coded. Locations included in the air, on the desk or other surfaces, or on one’s hand. Hand use could be right hand, left hand, or both hands. Symmetry recorded whether a symmetric gesture was observed. Looking at hands was recorded positive when the participant glanced at their hands at least once while gesturing. At last, the time spent on gesturing at study and at test for each stimulus was coded.

**Inter-rater reliability.** Two trained coders coded 9 of the 50 videos from the GA condition for representational gestures, location (air, desk, hand), gesture hand, gesture hand symmetry/asymmetry, looking at hands, time gesturing at study and test, reading time at study and test. Upon passing the reliability test, the two coders coded the rest of the 41 videos with equal workload. Reliability was assessed with Cohen’s kappa and, for binary variables, Maxwell’s RE. For the key measure, representational gestures, Kappa = .937 (p < .001), Maxwell’s RE = .938; for all other variables, agreements were high and significant at the p < .001 level, as shown in Table 1. A paired t-test for 3 randomly selected videos showed no differences in coding of gesture time at study ($t(23) = -0.227, p = 0.784$) and study time ($t(23) = 1.963, p = 0.062$).

<table>
<thead>
<tr>
<th>Gesture Behavior</th>
<th>Cohen’s Kappa (p-values)</th>
<th>Maxwell’s RE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Representational Gesture</td>
<td>0.937 (&lt;0.001)</td>
<td>0.938</td>
</tr>
<tr>
<td>Location (Air)</td>
<td>0.567 (&lt;0.001)</td>
<td>0.600</td>
</tr>
<tr>
<td>Location (Desk)</td>
<td>0.966 (&lt;0.001)</td>
<td>0.969</td>
</tr>
<tr>
<td>Location (Hand)</td>
<td>0.528 (&lt;0.001)</td>
<td>0.785</td>
</tr>
<tr>
<td>Hand Use (Right)</td>
<td>0.938 (&lt;0.001)</td>
<td>0.938</td>
</tr>
</tbody>
</table>
Hand Use (Left)            0.872 (<0.001)          0.877  
Symmetric                 0.797 (<0.001)          0.908  
Asymmetric                0.780 (<0.001)          0.785  
Looked at hands           0.743 (<0.001)          0.877  

**Excluded data.** If participants skipped a text without reading it (usually a result of the screen being advanced due to noise rather than participant request), data for that participant for that text was removed from analysis. In addition, the arithmetic problems were added after approximately 10% of the participants had already completed the experiment, so there are slightly fewer participants for the arithmetic problems than for the six texts.

**Gesture behavior.** Participants who were assigned into the Gesture Prevented group did not always follow the instructions. Since 33.3% of participants in the Gesture Prevented condition gestured, a new group of participants emerged: Gesture Prevented but Observed (GPO).

84% (42 out of 50 participants) of the participants in the Gesture Allowed group gestured for at least one text. The order of the texts (easy to hard vs. hard to easy) affected the number of texts the participant gestured for. Participants gestured for more texts when they studied easier texts first ($t(43.424)=2.012$, $p=0.050$, as shown in Figure 1).

![Error bars: 95% CI](image)  

*Figure 1. The frequency of gesture behavior in the Gesture Allowed condition.*
**Location.** The location of participant gestures was recorded and analyzed. In the case of a participant gesturing in multiple locations, both locations were counted. For linear orders, it appears that the air and on a surface were the most common locations for gesturing. A similar pattern emerged for the schedules; in addition, schedules resulted in the highest proportion of gestures on hand. See Figure 2.

![Figure 2. Location of gestures for each text.](image)

For many participants, using their hands as a matrix or table to keep track of the schedules was a common practice. For the mechanical systems, the most common gesture location was in the air. This is logical because the texts described three-dimensional objects in space. Conversely, gesturing on one’s hand during the mechanical systems was rare, likely because it is difficult to model three-dimensional objects on a hand. During arithmetic problems, participants gestured on a surface most often, and could typically be observed “writing” numbers out with their fingers. This action along with counting also was observed in the air. See Figure 3.
Hand use. Gestures performed during the six texts (linear orders, schedules, and mechanical systems) most often utilized both hands. Arithmetic problems resulted in mainly right hand use, likely because participants were “writing” numbers with their dominant hand, as shown in Figure 4.

Symmetry. Symmetric gestures are any gestures in which the right and left hands are performing the same, mirrored gestures. Symmetric gestures were most prominent during mechanical systems. This is likely a result of participants modeling parts of the systems that are symmetric in nature (e.g. handles of the bike pump). See Figure 5.
Figure 5. Use of symmetric gestures.

Looking at hands. Most participants did not look at their hands while gesturing. In the case that a participant looked at their hands at least once per text, this was coded as an observation of looking. In this study, looking at hands was least common during mechanical systems, as shown in Figure 6. This may be a result of the abstract and complex nature of this stimuli. However, a fair number of participants were observed looking at gestures during linear orders and schedules, perhaps because these are able to be visualized more easily. And when filling information in the spatial models, the location of the entries is important. Looking at hands was most common during the multiplication problem. This may be directly linked to participants’ strategy of “writing” with their fingers – participants likely looked down at their hands to imagine numbers in place.

Figure 6. Looking at hands at least once by text.
**Bilingual.** Previous work has shown that bilingual individuals gesture more than monolingual individuals (Nicoladis, Pika, & Marentette, 2009). Within GA condition, a Chi-square test of independence was calculated comparing bilingual status and whether participants gestured (for at least one text). No significant interaction was found ($\chi^2 (1) = 1.643, p = 0.255$).

**Gender.** Were participants of one gender more likely to gesture than another? A Chi-square test of independence was calculated comparing gender and whether participants gestured. No significant interaction was found ($\chi^2 (1) = 0.005, p = 0.942$).

**Accuracy.** The accuracy for each statement and arithmetic problem was either 0 (incorrect) or 1 (correct). Test accuracy for each text was calculated by summing up the score of the correct true/false statements and dividing the number by the total number of the statements of that text. Thus the accuracy of the texts was a number from 0 to 1.

**Accuracy by condition groups.** The accuracy comparison used the adjusted groups: Gesture Allowed (GA), Gesture Prevented (GP) and Gesture Prevented but Observed (GPO). The result revealed significant differences for the mechanical systems: bike pump $F(2, 115)=5.255, p=0.007$ and car brake $F(2, 116)=5.256, p=0.007$. The remaining texts did not result in significant differences: countries $F(2, 114)=2.313, p=0.104$; movies $F(2, 115)=0.490, p=0.614$; sports $F(2, 115)=0.358, p=0.700$; events $F(2, 114)=1.931, p=0.150$; addition $F(2, 102)=2.006, p=0.140$; multiplication $F(2, 101)=0.727, p=0.486$.

A follow-up comparison was done to examine the differences amongst the three conditions for bike pump and the car brake, as shown in Figure 8. For the bike pump text, a Bonferroni test of multiple comparisons revealed that the accuracy was higher for GA condition than both the GP ($p = 0.027$) and GPO ($p = 0.022$) conditions. There was no significant difference in accuracy between the GP and GPO groups ($p=1.000$).
For the car brake text, a Bonferroni test of multiple comparisons revealed that the participants in the GA condition performed better than those in the GPO condition (p=0.005). No significant difference was observed between the GP and GA groups (p=0.325) or between the GP and GPO groups (p=0.188). See Figure 7.

Figure 7. Average accuracy by condition for mechanical systems (error bars indicate 95%CI).

**Accuracy by spatial ability rating.** Each participant rated their spatial thinking ability in the post questionnaire from 1 to 5 with higher score indicating better spatial ability. Participants who rated their spatial ability higher performed better on schedules (Sports: F(4, 113) = 5.129, p = 0.001; events: F(4, 112) = 9.424, p < 0.001), mechanical systems (Bike Pump: F(4, 113) = 3.136, p = 0.017; Car Brake: F(4, 114) = 4.984, p = 0.001), and addition (F(4, 100) = 2.822, p = 0.029), consistent with previous research (e.g., Tversky, Heiser, & Morrison, 2013).

**Exclusion of non-gesturers.** To examine the effect of gestures, 8 participants who didn’t gesture in any of the text in GA group were excluded. The accuracy of the remaining 42 cases were compared with the performance of the GP group. Participants in the GA condition still showed higher accuracy than the GP condition on bike pump (F(1,62)=5.897, p=0.018) and car
brake (F(1,63)=12.324, p=0.001). In addition, the result also showed higher accuracy for the gesture allowed participants on Countries with F(1,62)=4.327, (p=0.042). The results indicate that when gestures were used during the experiment, the accuracy of the true/false questions is significantly higher in counties, bike pump, and car brake. Significant differences between GA group who actually gestured and GP participants are not found in the movies, sports, events, or arithmetic problems.

**Accuracy by behavior.** For a further break down of the groups based on participants’ gesture behavior on each text, four subsets were created to test the effect of behavior on performance: G_O (GA condition, gesture observed), G_N (GA condition, did not gesture), N_N (GP condition, did not gesture), and N_O (GP condition, gesture observed). Each participant has 8 entries of data corresponding with the 8 texts and math problems. In this way, we managed to group the cases by both the original assignment and their actual behavior.

ANOVA was performed for a comparison of performance amongst the four groups by text type. The mechanical systems, once again, higher accuracy scores were found for gesturing on bike pump F(3,114)=3.777, (p=0.013) and car brake F(3,115)=2.750, (p=0.046). No significant differences for accuracy were found for any of the other texts.

Follow-up t-tests were performed to compare performance for various behaviors on accuracy. Significant differences were found between the following behavior groups for the bike pump (Figure 8): G_O and N_N (t(88)=2.480, p=0.015); G_O and N_O (t(36)=2.493, p=0.017); G_N and N_O (t(26)=2.419, p=0.023). Significant higher scores were found for the gesture allowed participants over the gesture prevented participants for the car brake (Figure 9): G_O and N_N (t(86)=2.130, p=0.036); G_O and N_O (t(41)=2.757, p=0.009).
Figure 8. Average accuracy by behavior groupings for Bike Pump.

Figure 9. Average accuracy by behavior groupings for Car Brake.
**Gesture Times.** This section analyzed time duration at study and test, and time spent gesturing during study and test for each text. A closer exploration was taken for the interactions between gesture times and other variables.

**Study times.** Time spent studying each text did not significantly differ amongst participant conditions (GP, GA, GPO): countries F(2, 114)=0.712, p=0.493; movies F(2, 115)=1.288, p=0.280; sports F(2, 115)=0.492, p=0.613; events F(2, 114)=0.689, p=0.504; bike pump F(2, 115)=0.303, p=0.739; car brake F(2, 116)=0.272, p=0.762; addition F(2, 102)=0.184, p=0.833; multiplication F(2, 102)=0.267, p=0.766. Although the GA and GPO participants were gesturing while reading, this additional action did not extend their study time.

![Time spent at study and time spent gesturing during study.](image)

**Gesture time at study.** The proportion of time spent gesturing during study for participants in the GA condition was highest for linear orders (countries: 53%; movies, 44%) and the multiplication problem (45%). Mechanical systems resulted in the lowest percentage of time gesturing at study, but the longest time gesturing overall. This is reasonable since only the mechanical systems repeated four times, which increased the time spent studying.
**Test times.** Time spent evaluating true/false statements for each text did not significantly differ amongst participant conditions (GP, GA, GPO): countries F(2, 114)=1.645, p=0.197; movies F(2, 115)=0.675, p=0.511; sports F(2, 115)=1.040, p=0.357; events F(2, 114)=0.089, p=0.915; bike pump F(2, 115)=2.546, p=0.083; car brake F(2, 116)=0.576, p=0.564; addition F(2, 102)=0.257, p=0.774; multiplication F(2, 101)=0.873, p=0.421. Just as with study, the act of gesturing in the GA and GPO groups did not significantly increase time spent at test.

**Gesture time at test.** The proportion of time spent gesturing during evaluation for participants in the GA condition was highest for linear orders (countries: 32%, movies: 36%). This percentage may be considerably larger than for schedules and mechanical systems because linear orders only included six true/false statements, whereas schedules and mechanical systems included sixteen true/false statements. The percent of time spent gesturing during test was especially low for arithmetic problems; participants were able to choose the correct answer from a multiple choice list, which likely happened quickly as a result of low demands on working memory. The researchers believe that longer response times for arithmetic typically occurred when participants were expecting to see an answer that was not an option.

![Figure 11. Time at test and time gesturing at test for each text in Gesture Allowed condition.](image-url)
Gesture behavior and reaction time. Gesture at study was found to lower evaluation time at test. In the GA group, there are four conditions of gesture behavior: (1) no gesture at study and no gesture at test, (2) gesture at study and no gesture at test, (3) no gesture at study but gesture at test, and (4) gesture at both study and test. To examine whether gesture at study would shorten the time at test, time duration at test was compared for people who gestured at study and those who didn’t. Neither group gestured at test. A Chi-square test of independence was calculated to demonstrate that gesture behavior at study is independent of the type of text; no significant interaction was found ($\chi^2 (7)=13.443, p=0.062$). An ANOVA was performed to compare evaluation time by gesture behavior at study. A significant difference was found ($F(1,270)=9.695, p=0.002$). Participants who gestured when studying the text used significantly less time at test. Thus, modeling gestures had a positive effect on memory and led to faster retrieval in the recall task.

Figure 12. Average time at test is significantly lower for Gesture Allowed participants who gestured at study than for those who did not gesture at study.
**Difficulty and Time.** Did the order of difficulty of the texts (easy to hard; hard to easy) influence time spent at study or evaluation, or time spent gesturing at study or evaluation? For three of the texts, the time spent studying was longer when the difficulty order was hard to easy: movies F(1, 116)=14.000, p<0.001, bike pump F(1, 116)=8.873, p=0.004, car brake F(1, 117)=7.222, p=0.008.

Similarly, time spent evaluating true/false statements was longer when the difficulty was hard to easy for the following three texts: bike pump F(1, 116)=13.540, p<0.001, car brake F(1, 107.587)=9.115, p=0.003. It should be noted that the car brake failed Levene’s Test of Homogeneity. Therefore, the Welch statistics is used. The length of the texts and the number of true/false statements are similar for the easy texts and the practice task. It is possible that if the participant starts with the easy texts, participants have already become accustomed to a text of this length. However, when difficult texts come first, participants require additional time to adjust to the task.

For participants in the GA condition, there was no significant difference for time spent gesturing during study or test between the two difficulty conditions. Most of the additional time spent at study and evaluation for the hard to easy condition might be spent on reading and adjusting to the task. Gestures may come after the participants were comfortable and confident enough to focus on comprehending and memorizing the texts.

**Questionnaire Data.** A post-experiment questionnaire was distributed to all participants. This questionnaire asked about the perceived difficulty of each text type, strategies used for remembering (GA condition only), beliefs about gesture (GA condition only), and feelings about sitting on their hands (GP condition only).
**Difficulty rate.** Participants were asked to rate the difficulty of each text type on a Likert scale from 1 (very easy) to 5 (very difficult). As predicted, linear orders were rated the easiest (M=2.437, SD=1.055), schedules were rated moderately difficult (M=3.168, SD=1.076), and mechanical systems were rated the most difficult (M=4.168, SD=0.942). Ratings between participant conditions were not significantly different for any of the text types: linear orders t(117) = –1.80, p=0.74; schedules t(117) = –1.847, p=0.067; mechanical systems t(117) = 1.066, p=0.288. In other words, participants in one condition did not perceive any text type to be more or less difficult than participants in the other condition.

**Strategies.** Participants in the GA condition were asked to identify strategies that they used while studying and recalling information from each text type. They were given a list of strategies (gesture, mental map, text memorization, mnemonic device, other), and were permitted to select more than one strategy. All results are presented as recorded, with the exception of one participant who described a gesture behavior as “other”; this participant’s strategy was adjusted to reflect that they had used the gesture.

While gesture was a popular strategy across all three texts, the most common self-reported strategy was mental mapping. Earlier results indicated that 16% of participants in the GA condition did not gesture at all. Further, not all participants in the GA condition gestured for all texts. Therefore, the results of this self-report are not surprising.
Beliefs about gesturing. Participants in the GA condition were asked to rate their beliefs about the following statement, ranging from strongly disagree (1) to strongly agree (5): “Gesturing helps understanding or remembering.” Responses were collected for 34 of the 50 participants in the GA condition, and suggest that participants do believe gestures are helpful for comprehension and memory. This explains the number of participants who were observed using gesture during at least one of the texts (84%).
Sitting on hands. Participants in the GP condition were asked to rate their beliefs about the following statement, ranging from strongly disagree (1) to strongly agree (5): “Sitting on your hands / restricting movement made it harder to understand and remember information.” Responses were collected for 51 of the 69 participants assigned to the GP condition (before any had been moved to the GPO condition).

Results indicate that three-quarters of participants surveyed (74%) agreed that sitting on their hands was restrictive. This response helps explain why one-third of the participants in the GP condition began gesturing at some point, and subsequently formed a new group of GPO participants.

The questionnaire included an additional, open-ended question for participants in the GP condition: “Did sitting on your hands interfere with studying the descriptions? If so how?” Participant answers helped to inform exactly how and when sitting on their hands was disadvantageous. For example, one participant responded: “Yes because [in] some cases I wanted to use my hands to model out or draw in the air some of the descriptions especially the mechanical ones.” It was not unusual for participants to express the desire to write or draw. Other participants directly stated that using their hands helps them to think: “Yes I was unable to use my fingers or hands as a means to structure my thinking.” Several participants also commented that sitting on their hands for such a long period of time became uncomfortable.

Conclusion

Previous research had shown that spontaneous gestures while reading complex spatial information improved comprehension and memory. Spatial descriptions are naturally mapped to gestures as they are actions and marks in space similar to diagrams. The present experiment extended that research to descriptions that were not inherently spatial, namely descriptions of
linear orders, temporal schedules, mechanical systems, and arithmetic. Although not inherently spatial, these sets of concepts can be diagrammed, which are mappings to space. In the present study, one group of participants was free to gesture and another was directed to sit on their hands. Gesture was not mentioned in the instructions. In fact, most participants allowed to gesture, and many told to sit on their hands, did make gesture models of these situations. The facts that participants spontaneously gestured and that their gestures modeled the relations among the concepts they were studying indicates that people believed their gestures helped their understanding.

Gesturing did improve comprehension and learning as assessed by T/F tests but only for the mechanical systems, the workings of a car brake and a bicycle pump. These systems were rated as most difficult, and in fact, required interrelating many different parts in an intricate causal chain, where the causal relations kept changing. This kind of comprehension contrasts with the temporal and linear orders required to learn the linear orders and schedules. In those, elements were lined up on a mental line, and the relations between them were constant for each case. The relational information for these cases, linear orders and schedules, is far simpler than that of the causal systems or, for that matter, the spatial environments. Establishing a mental representation of each spatial environment entailed integrating part-by-part a complex web of spatial relations going in two directions. This also explained why gestures helped more for functional relations than static (structure) information.

However, even in the cases where there was no gesture advantage in the T/F questions, gesturing at study did speed responding at test. This suggests that the T/F tests might not be sensitive enough to detect a gesture advantage. Faster responding does indicate better integration of the relations into an overall mental representation and gesturing supports that.
Why does gesturing models of the material to be learned while studying help people comprehend and remember complex relational information? Several factors seem at play. The information was verbal, and gesturing provides a second code; two codes are better than one (e.g., Paivio, 1986). But gesturing is a privileged code: gesturing can map complex relational information to space and to actions of the body, a more direct mapping of ideas than mapping to words, which bear arbitrary relations to meaning. Finally, gesturing embeds that information in the body as well as the brain.
CHAPTER IV STUDY 2
GESTURES FOR DIAGRAMS AND DESCRIPTIONS

Introduction

According to theories of grounded and embodied cognition, information processing is sensorimotor for human (Barsalou, 2008; Glenberg, 1997). Thus, gestures as a form of situated action play central roles in cognition. There is a growing body of research on the effect of spontaneous gestures on thought and communication in facilitating problem-solving, spatial cognition, second language learning or social interaction (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001; Cook, Mitchell & Goldin-Meadow, 2008; Cook, Yip & Goldin-Meadow, 2012; Chu & Kita, 2011; Tellier, 2005). Amongst the theories of the benefits of gesture in cognitive activities, Hostetter and Alibali (2008) claimed that representational gestures promote thinking and speech by creating mental images. Another theory that shares the same perspective is the Lexical Access Hypothesis (Krauss, Chen, & Gottesman, 2000). This theory hypothesized that gestures help in word retrieving when forming speeches. Speakers need gestures to create visual representations for spatial-motor concepts. Follow the logic of these theories that considering gestures as a facilitator for mental imagery, gestures are beneficial when visualizing text or other abstract information. If the information is already presented visually such as maps and diagrams, gestures are unnecessary in understanding and retrieving. However, it is common to see people use gestures when learning diagrams and navigating on maps. In addition, in Study 1 and our previous studies on gesture for thinking, it was observed that people rarely looked at their hands when gesturing, indicating that gesture was not a visual assistant when learning the content.

The present study explores whether people use gestures for visual stimuli and if they do whether gestures facilitate understanding and memory. The stimuli in this study were adapted
from the text and diagrammatic description that used in previous studies (Taylor & Tversky, 1992; Emmorey, Tversky, & Taylor, 2000; Kang et al., 2015). The majority of participants gestured in previous studies under instruction or spontaneously. Representational gestures were observed when participants studying the text or describing the systems from memory.

In this study, it is hypothesized that people gesture for diagrams as much as for text descriptions. And the gestures represent the content that are presented in diagrams. Finally, gesturing promotes learning texts and diagrams.

Since the previous studies have examined the nature of gesture and the effects of gesturing for descriptions of environments and mechanical systems, this study only adopted environment maps and mechanical system diagrams and the correspondent text descriptions.

**Methods**

**Participants.** 84 adults from Columbia University and affiliates were recruited in this study. Only students who graduated from a high school in the US or Canada and who do not have university-level courses in physics or engineering were included. Physics and engineering majors were excluded because they may inflate the scores on mechanical system stimuli.

One participant was excluded because he didn’t comply with the instructions. The rest of the 83 the participants have an average age of 26 years old, with a minimum age of 18 years and a maximum age of 58 years. 77% of the participants were female (64 females, 19 males). 87% of the participants were right-handed (72 right-handed, 9 left-handed, and 2 ambidextrous). 61% of the participants were bilingual (51 bilingual, 32 monolingual).

**Materials.** There were four trials of diagram/text learning task. Each task was followed by true/false statements as a memory test. There were two environment learning tasks and two mechanical system tasks in the experiment. Each trial was either presented in text or diagram
form. For each environment task, there were 20 true/false statements in the test. The test set contains 4 verbatim statements and 6 inference statements from the survey perspective, and 4 verbatim statements and 6 inference statements from the route perspective. For each mechanical system task, there were 16 true/false statements in the test, including 8 structure statements and 8 function statements. The environment maps and descriptions were adopted from an early study by Taylor and Tversky (1992) with permission. One was a map of a small town with 13 landmarks including roads and natural landscape. The other was the layout of a convention center. There were also 13 landmarks, but all of them are compacted in a rectangular space.

The diagrams and text descriptions of the mechanical systems have been used in many studies (Heiser & Tversky, 2006; Kang et al, 2012). The text descriptions were used in Study 1. The diagram of the bicycle pump included six components and used arrows to show action and the direction of air moving in and out of the pump. The diagram of the car brake also included six components and used arrows to present the action of each part and the moving directions of the brake fluid.

In this study, there were two types (environment and mechanical system) and two formats (diagram and text description) of stimuli. Therefore, to make sure that each participant study the environments and mechanical systems in both diagram and text format, a Graeco-Latin Square design was used to counter-balance the material. For a design with two sets of orders, that is format and types in our case, the Graeco-Latin square, also known as orthogonal Latin square, can maximize the efficiency of statistical investigation and minimize the order effect (Wald, 1943).
Since there were 2 formats of descriptions in each of the two types of stimuli, and each
description could be presented in either diagram or text form, there were 16 different orders of
the stimuli, as shown in Table 2.

Table 2 The arrangement of the Graeco-Latin square

<table>
<thead>
<tr>
<th>Stimuli Name</th>
<th>Town</th>
<th>Convention Center</th>
<th>Bike Pump</th>
<th>Car Brake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Letter Code</td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>D</td>
</tr>
<tr>
<td>Array #</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>01</td>
<td>Ad</td>
<td>Bt</td>
<td>Cd</td>
<td>Dt</td>
</tr>
<tr>
<td>02</td>
<td>Ct</td>
<td>Dd</td>
<td>At</td>
<td>Bd</td>
</tr>
<tr>
<td>03</td>
<td>Dd</td>
<td>Ct</td>
<td>Bt</td>
<td>Ad</td>
</tr>
<tr>
<td>04</td>
<td>Bt</td>
<td>Ad</td>
<td>Dd</td>
<td>Ct</td>
</tr>
<tr>
<td>05</td>
<td>At</td>
<td>Bd</td>
<td>Ct</td>
<td>Dd</td>
</tr>
<tr>
<td>06</td>
<td>Cd</td>
<td>Dt</td>
<td>Ad</td>
<td>Bt</td>
</tr>
<tr>
<td>07</td>
<td>Dt</td>
<td>Cd</td>
<td>Bd</td>
<td>At</td>
</tr>
<tr>
<td>08</td>
<td>Bd</td>
<td>At</td>
<td>Dt</td>
<td>Cd</td>
</tr>
<tr>
<td>09</td>
<td>Ad</td>
<td>Bt</td>
<td>Ct</td>
<td>Dd</td>
</tr>
<tr>
<td>10</td>
<td>Ct</td>
<td>Dd</td>
<td>Ad</td>
<td>Bt</td>
</tr>
<tr>
<td>11</td>
<td>Dd</td>
<td>Ct</td>
<td>Bd</td>
<td>At</td>
</tr>
<tr>
<td>12</td>
<td>Bt</td>
<td>Ad</td>
<td>Dt</td>
<td>Cd</td>
</tr>
<tr>
<td>13</td>
<td>At</td>
<td>Bd</td>
<td>Cd</td>
<td>Dt</td>
</tr>
<tr>
<td>14</td>
<td>Cd</td>
<td>Dt</td>
<td>At</td>
<td>Bd</td>
</tr>
<tr>
<td>15</td>
<td>Dt</td>
<td>Cd</td>
<td>Bt</td>
<td>Ad</td>
</tr>
<tr>
<td>16</td>
<td>Bd</td>
<td>At</td>
<td>Dd</td>
<td>Ct</td>
</tr>
</tbody>
</table>

(d = diagram, t = text)

When applied to the two gesture conditions, each order was repeated, once with a Gesture
Allowed participant and once with a Gesture Prevented participant. The assignment of the
condition for the odd-numbered participant was determined by a random number generator. For
example, for Participant 11, the random number generator was used to produce a random integer
between 0 (Gesture Prevented) and 1 (Gesture Allowed). In this experiment, the result was 1,
thus Participant 11 was assigned to Gesture Allowed group and the matching even-numbered Participant 12 was assigned to Gesture Prevented condition.

**Procedure.** Upon arrival, participants first signed the IRB Informed Consent and Participants Rights documents. The participants were asked to give permission for video and audio recording during the experiment to continue to participate.

The experimenter introduced the voice-controlled experiment software to the participant. In both groups, participants first finished a practice trial with one text description and one diagram to learn the nature of the test. The text trial was followed by four true/false statements and the diagram trial was followed by six. The text was a description of navigating in an amusement park. The diagram depicted the human circulatory system. Participants in the Gesture Prevented condition were asked to sit on their hands during the tasks, both verbally by the experimenter and by the on-screen instruction before each task. The participant was left alone in the room during the practice trials. Once the practice was completed, the experimenter returned to the lab and made sure that the participants had no questions about the experiment. Then the experimenter started the true tasks and left the room again. Instructions on the screen for Gesture Allowed condition would be like:

“The next diagram/text will be the map/description of a small town. As before, you will have as much time as you need to learn the diagram/text. When you are finished studying and ready to evaluate statements about the environment, say ‘next.’ Evaluate each statement as either ‘true’ or ‘false.’”

Instructions for Gesture Prevented group included an extra note that reminded the participants to sit on their hands:
“The next diagram/text will be the map/description of a small town. As before, you will have as much time as you need to learn the diagram/text. When you are finished studying and ready to evaluate statements about the environment, say ‘next.’ Evaluate each statement as either ‘true’ or ‘false.’

Before we begin, please sit on both of your hands. Please remain seated this way for the entirety of the experiment.”

The participants completed the four trials of the experiment in their own pace. Each description was repeated four times in a role before proceeding to the true/false statements. Once the participants had finished evaluating all the statements, the experimenter returned to the room. The participants were then given a post questionnaire about themselves and their reflection of the experiment. After the questionnaire, the experimenter thanked the participants and either paid them $10 or register them one hour of study credit towards a course.

**Equipment.** The instructions, diagram/text descriptions, and true/false statements were programmed in SuperLab 5.0 and presented to participants on an Apple iMac desktop computer. Their answers to the true/false statements were collected by the screen recording video with QuickTime software. To record the gestures, the webcam on the desktop computer recorded from the front angle and a second camera was set at the left side of the participants on a tripod for a side angle and larger visual field.

The survey data was collected through Google Forms. No names or email addresses were collected in the form. Participant IDs were used to identify the participants, and only the experimenter has access to the material that can match Participant IDs and the names.

**Results and Discussion**
**Participants.** Participants in the Gesture Allowed and Gesture Prevented conditions did not differ significantly on age (t(81) = -0.191, p = 0.849), bilingual ($\chi^2(1) = 0.665, p = 0.501$), gender ($\chi^2(1) = 0.041, p = 1.000$), and dominant hand ($\chi^2(2) = 1.044, p = 0.593$).

**Gesture coding.** Gestures were coded in ELAN software (European Distributed Corpora Project Linguistic Annotator), which is developed by Max Planck Institute for Psycholinguistics. Only representational gestures were coded and analyzed in this study. Under the representational category, point and tracing gestures were emphasized when participants studied diagrams and maps. As introduced in Study 1, gestures that presenting the shape, structure, order, or relations were categorized as representational gestures (McNeil, 1992). A gesture was marked as point and tracing when the gesture was performed in the air with fingers pointed to the screen, following the routes or directions on the map or the diagram. Other movements such as fidgeting were not counted as gestures.

In addition to the categories of gesture, a series of gesture features were also coded, including hand use (left hand, right hand, or both), location of the gesture (in the air, on the surface, on hand), symmetry (whether the gesture is symmetric or not), and looking at hands (whether the participants glanced at their hands at least once).

The time spent at study and test was logged for each stimulus. The time spent gesturing at study and test was also coded.

**Inter-rater reliability.** Two trained coders coded 8 randomly selected videos from the Gesture Allowed condition for the representational gesture features. As in Study 1, the binary variables were evaluated with both Cohen’s Kappa and Maxwell’s RE. Kappa values for representational gesture and a series of gesture features were all strong and significant at $p =$
0.001 level. Kappa was not calculated for “Location (Hand) because gesture performed on one’s hand was not observed and all values in this variable was a constant “0”.

Gesture time at study and test was assessed with a paired t-test. No significant difference was found between the two coders for time spent gesturing at study \( (t(63) = -0.534, p = 0.595) \) and at test \( (t(63) = -1.88, p = 0.07) \).

A single coder completed the gesture coding for the rest of the videos.

**Table 3. Inter-rater reliability for gesture coding**

<table>
<thead>
<tr>
<th>Gesture Behavior</th>
<th>Cohen’s Kappa (p-values)</th>
<th>Maxwell’s RE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Representational Gesture</td>
<td>0.955 (&lt;0.001)</td>
<td>0.958</td>
</tr>
<tr>
<td>Pointing &amp; Tracing</td>
<td>1.000 (&lt;0.001)</td>
<td>1.000</td>
</tr>
<tr>
<td>Location (Air)</td>
<td>0.863 (&lt;0.001)</td>
<td>0.917</td>
</tr>
<tr>
<td>Location (Surface)</td>
<td>1.000 (&lt;0.001)</td>
<td>1.000</td>
</tr>
<tr>
<td>Location (Hand)</td>
<td>NA</td>
<td>1.000</td>
</tr>
<tr>
<td>Hand Use (Right)</td>
<td>1.000 (&lt;0.001)</td>
<td>1.000</td>
</tr>
<tr>
<td>Hand Use (Left)</td>
<td>0.929 (&lt;0.001)</td>
<td>0.958</td>
</tr>
<tr>
<td>Symmetric</td>
<td>1.000 (&lt;0.001)</td>
<td>1.000</td>
</tr>
<tr>
<td>Looked at hands</td>
<td>0.864 (&lt;0.001)</td>
<td>0.917</td>
</tr>
</tbody>
</table>

**Gesture behavior.** Since the stimuli used in this study are all spatial models or models that can be spatialized, the representational gesture is the main focus and will be described in detail. Beat gesture and point-and-tracing gesture will be discussed anecdotally.

**Representational gesture behavior.** Overall 54% of participants in Gesture Allowed condition gestured at least once. Participants gestured for diagrams as much as for the texts. There was no significant differences of the number of observed gestures between diagram and text for both environment \( (t(82) = -0.227, p = 0.821) \) and mechanical systems \( (t(82) = 0.436, p = 0.664) \), as shown in Figure 15.
Figure 15. Representational gesture behaviors by format showed participants gesture for diagrams as much as for texts.

Participants gestured more when reading texts describing the environment than mechanical systems ($t(82) = 2.464, p = 0.016$), as shown in Figure 16. When breaking down into gestures at study and at test, significant differences of observed gestures were found between environment and mechanical system descriptions at test in diagram format ($t(82) = 4.123, p < 0.001$), at study in text format ($t(82) = 2.713, p = 0.008$), and at test in text format ($t(82) = 3.360, p = 0.001$).

Figure 16. Participants gestured more for Environment descriptions than Mechanical Systems.
**Pointing and tracing.** For diagrams and maps, a few proportion of participants used pointing and tracing when studying the materials. 7 out of 42 participants in the Gesture Allowed condition used tracing gesture with 1 for the Town, 2 for the Convention Center, 3 for Bike Pump and Car Brake. All of these seven participants were also observed using modeling gestures for the diagrams and maps, that is to say, no one only used tracing without modeling.

**Gesture for Mechanical Systems.** Not actually shown in either text and diagram descriptions, the function and interactions of parts in the machines, which played important roles in understanding the mechanical systems, were depicted by words and arrows in a static way. Therefore, gestures for action were of great concern when coding representational gestures to see how participants transferred the static information into dynamic interactions. 11 out of 42 participants in GA condition were observed gesturing for actions at least once when doing diagram tasks at either study, test or both. The same number of participants were observed gesturing for actions for texts. The number of participants who performed action gesture and structure gesture for each task was shown in Figure 17.

![Figure 17](image_url)

*Figure 17. The number of participants who performed action gesture and structure gesture.*
Participants that used action gestures did slightly better in memory test than those who did not use such gestures ($0.71 > 0.68$), but there was no significant effect of action gestures at study on test accuracy ($F (1,166) = 0.449, p = 0.50$). However, it should be kept in mind that only a few numbers of participants used action gestures for each stimuli.

**Location.** For environment descriptions, the most common location of the gestures was on a horizontal surface. This is reasonable because locating the landmarks on the desk with hands was a popular strategy among the participants. More participants gestured in the air for mechanical systems because participants modeled the structure and function three-dimensionally. Pointing and tracing the diagram resulted in a higher percentage of gestures in the air for the diagrams than the texts in both environment and mechanical system descriptions. Gesture on hand was only observed once in the text description of the Town. In Study 1, gesture on hand was mostly observed in temporal schedule descriptions when participants created tables on their hands. This probably explain why participants didn’t gesture on hand a lot in this study because the information was not structured in that way.

![Figure 18. Location of representational gestures at study](image)

**Hand use.** Out of all gestured participants, more were observed using both hands at study and one hand at test for text descriptions. One potential explanation for this observation is
participants were more likely to use both hands to visualize and locate the landmarks for the environment and the symmetric structure and function for the mechanical systems. And once they remembered the information, one hand was sufficient to help recall the models. A higher percentage of gestures for the environment in diagram format at study was performed with one hand may be the result of participant pointing and tracing the routes on the maps. During the test, both hands were used for information retrieval when one hand was fixed as a landmark and the other hand was moving to navigate.

Figure 19. Hand use of representational gestures at study (left) and test (right).

Symmetry. Symmetric gestures were most common in Car Brake text descriptions at study (6 observations). It should be noted that the number of symmetric gestures was quite small at study and even smaller at test. Only one or two gestures were observed for each stimulus. The higher rate of observations in Car Brake at study may be the result of the symmetric nature of the structure of the Car Brake. Higher rate of symmetric gestures was also found for mechanical systems at study in Study 1.
**Looking at hands.** Glancing at hands was more common for environment than mechanical system descriptions both at study \( (t(166) = 8.489, p = 0.004) \) and test \( (t(166) = 23.359, p < 0.000) \). This is reasonable because participants tended to glance at their hands when they were using hands as landmarks when gesturing on the surface. They glanced at the hands to remember the relative locations of the landmarks. But for mechanical systems, gestures were more likely to be produced when participants were trying to visualize the structure and functions in their head. Looking at hands was not necessary. More participants glanced at their hands for the environment in text descriptions than the diagram at study \( (F(1, 82) = 5.125, p = 0.026) \). On the contrary, more looking at hands behavior was observed, though not statistically significant, for the maps of the environments at test. One potential explanation is diagram made it easier to build mental models of the environment at study than text descriptions and participants tended to remember the picture rather than building a new visual with their hands as in the text format. But when recalling the information, both hands were used to visualized the picture in mind and participants were more likely to look at their hands. This finding echoed the hand use observation above.

*Figure 20. More participants glanced at hand at least once when doing Environments than Mechanical Systems (error bars indicate 95%CI).*
**Time at study and test.** There was no significant difference in study time and test time between Gesture Allowed and Gesture Prevented conditions. There was significant difference in study time between diagrams and text descriptions for all four stimuli: Town ($t(81) = -6.962, p < 0.000$); Convention Center ($t(81) = -4.997, p < 0.000$); Bike Pump ($t(81) = -8.809, p < 0.000$); Car Brake ($t(81) = -5.934, p < 0.000$). No significant difference was found in test time between the different formats. This is reasonable because reading texts required more cognitive load and time than processing images. But all the statements were presented in text format, which required equal processing time for both diagrams and texts. When evaluating the statements, participants used longer time in environment descriptions in both diagram and text formats ($t(330) = 11.487, p < 0.000$). There were 20 statements for each environment descriptions and 16 statements for the mechanical systems. This could explain the excessive time participants used when evaluating environment statements.

![Figure 21. Participants used longer time when studying text descriptions](image)
Figure 2. Average time spent at test was longer for the Environments.

**Gesture times.** Participants spent more performing representational gestures for environment than mechanical systems during study ($t(163) = 3.714, p < 0.000$) and test ($t(166) = 5.376, p < 0.000$). No significant difference was found for time spent on beat gestures between the two types. When breaking down to different formats, the results showed that time spent on representational gestures at study was not significant under diagram format. However, time spent gestures at test was significant ($t(82) = 3.946, p < 0.000$). In text format, both time spent gesturing at study ($t(80) = 3.658, p < 0.000$) and test ($t(82) = 3.625, p < 0.000$) were significantly longer for environment descriptions. These findings are in line with the previous analyses on observed representational gestures between types of stimuli.

**Gesture behavior and reaction times.** In Study 1, it was found that for mechanical systems, participants spent less time at test if they gestured at study and not gestured at test. Following the protocol, time at test was compared between participants who only gestured at
study and those who did not gesture at all. No significant differences were found for any stimulus.

**Time gesturing at study and accuracy.** No causal relationship was found between time gesturing at study and test accuracy for any stimulus. However, there was significant correlation between test accuracy and time spent on representational gestures for the diagrams and maps ($r = 0.305$, $p = 0.005$), as shown in Figure 23.

![Format of the stimuli: Diagram](image)

**Figure 23.** Longer time spent on representational gestures at study led to higher test accuracy

**Accuracy and study time.** There was significant correlation between accuracy and study time in Town ($r = -0.344$, $p = 0.001$) and Car Brake ($r = 0.357$, $p = 0.001$) across gesture conditions. For the Town, however, longer study time led to lower accuracy. For Car Brake, more time spent at study led to a higher score. Breaking down by conditions, the correlations still hold, as shown in Table 4.

**Table 4.** Correlation between time spent studying and accuracy by gesture conditions.
## Accuracy by condition

No significant difference was found in accuracy between the Gesture Allowed and Gesture Prevented conditions for any of the four stimuli: Town $F(1, 81) = 0.642, p = 0.425$; Convention Center $F(1, 81) = 0.345, p = 0.559$; Bike Pump $F(1, 81) = 0.922, p = 0.340$; Car Brake $F(1, 81) = 1.517, p = 0.222$. The results failed to replicate the findings of Study 1, in which participants achieved significantly higher score on the mechanical systems.

![Accuracy by gesture conditions](image.png)

*Figure 24. Accuracy by gesture conditions.*
**Accuracy by format and condition.** Breaking down the mean accuracy of each stimulus by gesture conditions and formats, no significant differences were found for any stimulus in either diagram or text format.

![Figure 25. Accuracy by gesture condition and format.](image)

**Accuracy by behavior.** Since not all participants in the Gesture Allowed condition gestured and those who gestured did not gesture for all tasks, the Gesture Allowed condition can be broken down into two subgroups: Gesture Allowed, did gesture (G_A); Gesture Allowed, did not gesture (G_N). Each stimulus was one entry and coded based on the actual gesture behavior. Unlike in Study 1, only one Gesture Prevented participant in this study did not follow the instructions and used their hands. This single case was excluded from the analyses. Therefore, a comparison of accuracy could be conducted within three conditions: G_A, G_N, and N_N (Gesture Prevented, did not gesture). Remember participants in Gesture Allowed condition were free to use their hands. If they didn’t gesture, it can be assumed that they did not need gesture as much as those who gestured. Therefore, excluding G_N condition, an overall ANOVA across stimuli format and types compared between G_A and N_N condition was conducted. The result
showed significant effect of gesture behavior on test accuracy ($F(1, 253) = 4.012, p = 0.046$). Participants who gestured in Gesture Allow condition performed significantly better than the Gesture Prevented condition.

![Bar chart comparing mean accuracy between Gesture Prevented and Gesture Allowed & Observed conditions.](image)

**Figure 26.** Average accuracy of Gesture Allowed participants who gestured significantly higher than participants in Gesture Prevented condition (error bar indicate 95% CI)

However, when breaking down by formats and types of the descriptions, ANOVA showed no significant difference on accuracy among the three broken down gesture behavior conditions for any of the stimuli. Further analysis that broke the data by format did not show significance on accuracy across the three broken down conditions either.

**Questionnaire.** In the questionnaire at the end of the experiment, participants were asked to rate the difficulty of each task, to identify what strategies they used, and share their ratings and comments about sitting on hands or the belief of using hands during the study.

**Text difficulty rating.** No significant difference was found on difficulty rating between gesture conditions, indicating that the tasks were equal challenging for participants in the two conditions. Also, there was no significant difference in difficulty rating between gesture conditions by the format of the stimuli.
**Difficulty rating and accuracy.** Since the difficulty ratings were not normally distributed, instead of using Pearson’s correlation, the Spearman correlation was conducted to explore the relationship between difficulty rating and accuracy. There are significant correlations for the following stimulus and format: Town in diagram ($r = -0.314$, $p = 0.046$), Convention Center in diagram ($r = -0.488$, $p = 0.001$), Bike Pump in diagram ($r = -0.489$, $p = 0.001$), and Bike Pump in text ($r = -0.340$, $p = 0.037$). The rest of the correlations were not significant but were all showing negative correlations. These results indicate that the lower the ratings were, the higher the accuracy scores the participants achieved.

**Beliefs about the gesture.** More than 75% of participants agreed, including about 50% of participants in Gesture Allowed condition strongly agreed that gesturing helped understand and remember text and diagram descriptions, as shown in Figure 27 and 28.

![Figure 27. Belief about gesture for text descriptions. Participant responses: “Gesturing helps understanding or remembering text descriptions.”](image-url)
Figure 28. Belief about gestures for diagram descriptions. Participant responses: “Gesturing helps understanding or remembering map/diagram.”

**Sitting on hands.** More than half of the participants agreed, including 20% strongly agreed that sitting on hands made it harder to understand and remember text descriptions. For diagrams, however, only about 42% of participants agreed that sitting on hands made the tasks harder.

Figure 29. Opinion on sitting on hands for texts. Participant responses: “Sitting on my hands made it harder to understand and remember text descriptions.”
Conclusions

This study was designed to test two hypotheses: 1) People produce spontaneous gesture during study and test of spatial models that are presented in diagram or maps as frequently as text stimuli; 2) Gesture will improve comprehension and memory for spatial models that are presented in diagram.

The first hypothesis has been proved to be true in Figure 15. There was no significant difference on the frequency and time spent gesturing between diagrams and texts. People do gesture for information that is already presented in the visual spatial form.

The second hypothesis has been proved to be true when comparing the test accuracy across types and formats of stimuli between Gesture Allowed participants who actually gestured and participants in Gesture Prevented condition. However, when breaking down by stimuli, no significant effect was found for gesture behavior and memory test scores. In Study 1, gestures were found to be helpful for comprehension and memory on mechanical systems. This study did not replicate the results. Possible reasons may include but not limited to the small sample size of
each condition. This study was a 2x2 factorial design with two types of stimuli in two formats and two gesture conditions to assign the participants, making small samples for each sub-condition.

Except for the hypotheses, the study also found that people gestured more for environment descriptions than mechanical systems, as shown in Figure 16. Unlike mechanical systems, environment layouts are in two dimensions. People are more familiar with maps and layouts and used to navigate using lines and arrows. Mechanical systems, on the contrary, are models in the three dimensional world. There are no established spatial models for people to fit the description in. But once figured out a strategy, gestures would be performed for visualizing the structure and function of the systems.

For maps and diagrams, a small number of participants used pointing and tracing gestures when studying the materials. But no one only used pointing and tracing without modeling gestures.

**Implications**

This research focused on spontaneous gestures when people process information, not for the communicative purpose, but for self. This work broadened the research about gesture for thinking, when people gesture, what types of gestures they may produce, and whether gestures are beneficial in cognition and learning. Study 1 showed that people gesture not only for spatial models but also models that are not inherently spatial. Participants use gesture to visualize text descriptions, translating the non-spatial information into spatial models. What’s more, these gestures facilitate the comprehension and memory for some kinds of information (mechanical systems), making it easier for participants to understand the complex systems. Study 2 aims to complement the theory about the relationship between gesture and visual spatial information.
This study demonstrated that gestures not only can help visualize abstract information, but also be critical when people processing visual spatial models.

Not many researches discussed gestures for self and that makes this study more meaningful for a better understanding of human gesture behaviors. Unlike gestures for communication, spontaneous gestures are often abstract and incomplete. Coding gestures is a subjective and time-consuming job. Yet a well-designed coding scheme is the first step to interpret gestures. A good coding scheme cannot be too detailed to lose the common pattern of gestures and should not be too sketchy to not be able to catch enough information. Thus a good coding scheme is a well-balanced one. The coding scheme used in this research was developed to categorize the types (representational or beat), as well as to collect key features that can picture the pattern of the gestures and reveal the intentions of the participants.

Gesturing was found beneficial in some contexts, but not in others. For the environments and mechanical systems, gesturing showed a positive effect on comprehension and memory. However, participants gestured for all the texts and diagrams even though no significant improvement was found on the memory test for the text description of linear orders and the schedules. Gesturing at study also sped responding at test, indicating better integration of the information. In both studies, participants in the Gesture Prevented condition claimed that restricting hand movements made it harder to do the tasks, suggesting the facilitator role of gesture for self in learning.

Limitations

As for all laboratory experiment studies, there are always random factors that could interfere with the results. In Study 1, almost one-third of the participants in Gesture Prevented condition did not comply with the instructions and gestured. Some participants complained that
the desk and chair were uncomfortable. Some were ill and coughed badly during the test and skipped too many test statements. In Study 2, a few participants in Gesture Allowed condition reflected that even they had agreed to be video recorded, they still felt uneasy when they knew they were on camera. These random factors may or may not be significant enough to influence the results but it is too hard to identify.

Another limitation is the lack of statistical power due to the limited sample size. As discussed in the previous section. Even though 125 or 83 were a decent size for psychological science research, once breaking down to detailed conditions, the number of participants in each condition was small. Moreover, not every participant in the Gesture Allowed condition gestured, resulting in an even smaller available dataset for analysis of gesture behavior. In addition, the lack of diversity is also a limitation of the sample. Only students from Columbia University and affiliates were included in this research.

Last but not least, the measurement may not be efficient. The texts, diagrams, and statements were all classical materials in the field of gesture studies and have been tested in many scenarios. However, Study 2 was the first attempt to compare gestures for the diagrams or maps and text descriptions and each participant was asked to study stimuli in both formats. Alternative measures may be required to test the effect between gesture conditions for certain contexts.
REFERENCES


APPENDIX A

Study 1 Scripts

Written by Dr. Barbara Tversky.

<table>
<thead>
<tr>
<th>Gesture Condition</th>
<th>No Gesture Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welcome!</td>
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</tr>
<tr>
<td>This is a study of learning complex descriptions. You will study three kinds of descriptions, two examples of each. After studying each description, you will be presented with statements about the descriptions and you will judge whether each statement is true or false. Then you'll go on to the next description. Before each kind of description, you will be told what kind of description you'll be reading. You'll have as much time as you need to read the descriptions and evaluate the statements.</td>
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<td>You will progress from screen to screen using your voice. To advance, say &quot;next.&quot; When you get to the true/false statements, give your answer, &quot;true&quot; or &quot;false&quot;. After you have answered, the next question will appear on the screen. When you have answered all the questions for that description, a screen will appear telling you that. When you are ready, say &quot;next&quot; to see the next description.</td>
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</tr>
<tr>
<td>Let's start with a practice trial. On the next screen, you'll study a description of an imaginary environment. When you're done studying, you'll advance to the next screen for the first question. There will be 4 questions for this description. The experimenter will be outside the room while you go through the practice trial. When you're done, please open the door to call the experimenter back into the room.</td>
<td>Before we begin, please sit on both of your hands. Please remain seated this way for the entirety of the experiment.</td>
</tr>
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</tr>
<tr>
<td>[Insert practice text / statements]</td>
<td>To begin, say “next.”</td>
</tr>
<tr>
<td>Practice Trial Complete!</td>
<td>[Insert practice text / statements]</td>
</tr>
<tr>
<td>You have now completed the practice text. Please open the door to call the experimenter back into the room.</td>
<td>Practice Trial Complete!</td>
</tr>
</tbody>
</table>
You have now completed the practice text. Please open the door to call the experimenter back into the room.

The next two descriptions will be of items that are ordered in one way or another. As before, you will have as much time as you need to read each description. When you are finished reading and ready to evaluate statements about the text, say “next.” Evaluate each statement as either “true” or false.

The next two descriptions will be about schedules of events. You will have as much time as you need to read each description. When you are finished reading and ready to evaluate statements about the text, say “next.” Evaluate each statement as either “true” or false.

The next set of two descriptions will be of mechanical systems. Each description will be in two parts on separate screens. For each mechanical system, you will have four repetitions of the two parts. You will have as much time as you need to read each description. To get the next screen, say “next.” When you have finished reading the four repetitions of the two screens, say “next” to see the questions. Evaluate each statement as either “true” or false.

You have now completed this part of the experiment. Please open the door and call the experimenter back into the room. Thank you for your participation!
APPENDIX B

Study 1 Texts

Practice Text

Americana World is a large amusement park based on US history and geography. It has a large parking lot leading to Revolution Path. You go west on Revolution Path and you will find the ticket booth on your right decorated with US flags. Past the ticket booth, you turn right on Arctic Highway.

Practice Text True/False Statements

- You go west on Revolution Path and you will find the ticket booth on your right decorated with US flags.
- Coming back from Arctic way, you turn left on Revolution Path and you will find the ticket booth on your right.
- West of the ticket booth, the Arctic Highway goes south from Revolution Path.
- The parking lot is east of the ticket booth.
Linear Order: Movies Text

Alex loves movies. He prefers spy movies to romance. He likes drama less than spy. He likes comedies more than spy movies. He prefers romance to drama.

Movies Text True/False Statements

- Alex likes spy movies more than drama.
- Alex likes comedies less than romance.
- Alex likes drama more than romance.
- Alex likes spy less than comedies.
- Alex likes romance less than spy.
- Alex likes drama more than comedy.
Linear Order: Economics Text

A group of economists were asked to make predictions for economic growth for Latin American countries for the next 10 years. They predicted Mexico’s growth higher than Argentina’s, Mexico greater than Brazil, Brazil less than Cuba, Argentina less than Brazil, and Cuba higher than Mexico.

Economics Text True/False Statements

- Cuba’s growth should be lower than Mexico’s.
- Brazil’s growth should be lower than Cuba’s.
- Cuba’s growth should be higher than Argentina’s.
- Mexico’s growth should be lower than Brazil’s.
- Mexico’s growth should be higher than Argentina’s.
- Argentina’s growth should be higher than Brazil’s.
Schedule: Occasions Text

The Amazing Occasions Company is coordinating three celebrations for the weekend. For the Birthday Celebration, dinner will be at 6:00 pm, toasts at 7:00 pm, and a slide show at 8:00 pm. For the Wedding Party, they plan to have dancing at 6:00 pm, dinner at 7:00 pm, and toasts at 8:00 pm. For the Exhibit Opening, there will be a slide show at 6:00 pm, dinner at 7:00 pm, and dancing at 8:00 pm.

Occasions Text True/False Statements

- All the events have dinner at the same time.
- When there are toasts, they always follow the dinners.
- Dinner is at the same time for the Wedding and the Opening.
- For the Birthday and the Wedding, toasts are at the same time.
- Toasts for the Birthday are earlier than dinner.
- At the Birthday the slide show is after the toasts.
- At the Exhibit Opening, the slide show is after the dinner.
- Dinner comes before dancing for the Exhibit Opening.
- At the Wedding, dancing comes before the dinner.
- Dinner is later than the toasts at the wedding.
- The Wedding toasts come after the Birthday toasts.
- The Birthday slide show is before the Exhibit slide show.
- Dancing is earlier at the Exhibit Opening than toasts at the Wedding Party.
- Dancing at the Wedding is earlier than dancing at the Exhibit Opening.
- There are toasts at all the events.
- All of the events have dinners.
Schedule: Sports Text

Jon, Dan, and Ted are at sports camp and comparing their activities for the week. Jon plays soccer in the morning, baseball in the afternoon, and basketball in the evening. Dan does soccer in the morning, basketball in the afternoon, and swimming in the evening. Ted does swimming in the morning, baseball in the afternoon, and soccer in the evening.

Sports Text True/False Statements

- All the boys play soccer.
- The boys all swim.
- No one plays basketball in the morning.
- Swimming is always at night.
- Jon plays soccer after basketball.
- Jon plays baseball before basketball.
- Dan does basketball earlier than swimming.
- Dan plays soccer later than basketball.
- Ted swims before he plays baseball.
- Ted plays baseball after he plays soccer.
- When Jon is playing baseball, Dan is playing basketball.
- When Ted swims, Jon plays basketball.
- Dan plays soccer before Ted.
- Dan plays basketball after Jon.
- Ted swims before Dan plays basketball.
- Jon does baseball after Dan swims.
Mechanical System: Bike Pump

Structural Description:
The bicycle pump is a tall cylinder with a handle extending from the top that can move up and down. Attached to the bottom of the handle in the middle of the cylinder is the piston. Next to the piston is the inlet valve that can open and close. Below the inlet valve is the chamber. Extending outward from the chamber at the bottom is the outlet hose. Between the chamber and the hose is the outlet valve, which can open and close.

Functional Description:
When the handle is pulled up, it pulls the piston up. The pressure of the upward movement of the piston causes the inlet valve next to the piston at the top of the chamber to open and the outlet valve at the bottom of the chamber of the pump to close. This allows air to enter the lower chamber. When the handle is pushed down, pressure is exerted in the chamber causing the outlet valve to open. The pressure in the chamber and the opening of the outlet valve causes air to exit through the hose.

(Note: Each description type shown 4 times, creating this presentation pattern: S F S F S F S F)

Bike Pump Text True/False Statements
- The piston is attached to the wall of the cylinder.
- The inlet valve is open when the outlet valve is closed.
- The piston is at the bottom of the handle.
- The inlet valve opens when the handle is pulled up.
- The outlet valve extends outward from the piston.
- Pulling the handle up pulls the inlet valve up.
- Pushing the handle down closes the inlet valve.
- Pressure build up in the chamber opens the outlet valve.
- The downward movement of the piston causes the inlet valve to close.
- The outlet valve opens when the piston is raised.
- The outlet valve allows air to enter the chamber.
- The pump works when the outlet valve stays open.
- Next to the handle is the inlet valve.
- Next to the hose is the outlet valve.
- The outlet valve is between the chamber and the hose.
- The inlet valve is above the chamber.
**Mechanical System: Car Brake**

**Structural Description:**
The brake or brake drum is a circular structure. Directly inside the sides of the brake drum are two thick semicircular structures called the brake shoes. The brake fluid reservoir is located above and to the side of the brake drum. From the brake fluid reservoir, a tube runs down sideways and then down to the middle of the brake drum. Extending from both sides of the tube in the middle of the brake drum are wheel cylinders surrounding small pistons. Brake fluid can move from the reservoir through the tube to the pistons. The small pistons can move outward toward the brake shoes. The brake shoes can move outward toward the brake drum.

**Functional Description:**
From the brake fluid reservoir, brake fluid enters and travels sideways and down the tube. As the brake fluid accumulates at the bottom of the tube, pressure is exerted on the small pistons inside the wheel cylinders. This causes the pistons to push outward toward the brake drum. The outward movement of the shoes causes friction along the inside of the brake drum, slowing the rotation of the wheel.

(Note: Each description type shown 4 times, creating this presentation pattern: S F S F S F S F)

**Car Brake Text True/False Statements**
- Brake fluid can move to the brake shoe.
- The brake drum moves towards the brake shoe.
- The brake fluid reservoir is inside the brake drum.
- The wheel cylinders surround the small pistons.
- The small pistons are adjacent to the brake shoes.
- The pressure of fluid accumulation is exerted on the small pistons.
- The tube is next to the wheel cylinder.
- The wheel cylinders are next to the tube.
- Brake fluid pushes the brake drum outward.
- The brake shoes are circular devices.
- Next to the brake drum are the wheel cylinders.
- The tube penetrates the brake shoes.
- The pistons put pressure on the brake shoes.
- The brake fluid stays in the tube.
- The amount of brake fluid released determines time to brake.
- The upward movement of the brake shoe slows the rotation of the wheel.
APPENDIX C

Study 1 Questionnaire

Post Questionnaire

Section 1 (to be filled by the experimenter)

Participant ID: [fill-in]
Date: [pop-out calendar]
Condition:
  • 01 (GP)
  • 02 (GA)

Section 2 (to be filled by the participant)

Gender: [fill-in]
Date of Birth: [fill-in]
What is your dominant hand?
  • Right
  • Left
  • Ambidextrous
Are you bilingual?
  • Yes
  • No
How would you rate your spatial thinking abilities?
Poor 1 2 3 4 5 Excellent

QUESTIONS ABOUT THE DESCRIPTIONS (GESTURE PREVENTED CONDITION)

You studied 3 types of descriptions (linear order, schedule, mechanical systems). Please answer some questions about each.

Please rate the difficulty of linear order descriptions (economic growth, movie preference).
Very easy 1 2 3 4 5 Very Difficult

Please rate the difficulty of schedule descriptions (sports practice, events).
Very easy 1 2 3 4 5 Very Difficult

Please rate the difficulty of mechanical system descriptions (car brake, bike pump).
Very easy 1 2 3 4 5 Very Difficult

Did sitting on your hands interfere with studying the descriptions? If so, how?
[open response]
QUESTIONS ABOUT THE DESCRIPTIONS (GESTURE ALLOWED CONDITION)

LINEAR ORDER DESCRIPTIONS

Please answer some questions about the linear order descriptions (economic growth, movie preference).

When learning the descriptions with orders, what strategies did you use?

You may choose more than one.

- Gesture
- Mental map
- Text memorization
- Mnemonic device
- Other: [open response]

SCHEDULE DESCRIPTIONS

Please answer some questions about the schedule descriptions.

When learning the descriptions with schedules, what strategies did you use?

You may choose more than one.

- Gesture
- Mental map
- Text memorization
- Mnemonic device
- Other: [open response]

MECHANICAL SYSTEMS DESCRIPTIONS

Please answer some questions about the mechanical systems descriptions (car brake, bike pump).

When learning the descriptions with mechanical systems, what strategies did you use?

You may choose more than one.

- Gesture
- Mental map
- Text memorization
- Mnemonic device
- Other: [open response]
**APPENDIX D**

**Study 2 Scripts**

*Written by Dr. Barbara Tversky for the previous study and modified for this study.*

<table>
<thead>
<tr>
<th>Gesture Condition</th>
<th>No Gesture Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welcome!</td>
<td>Welcome!</td>
</tr>
<tr>
<td>This is a study of learning diagrams. You will study two kinds of descriptions, two examples of each. After studying each diagram, you will be presented with statements about the diagrams and you will judge whether each statement is true or false. Then you'll go on to the next diagram. Before each kind of diagram, you will be told what kind of diagram you'll be learning. You'll have as much time as you need to study the diagrams and evaluate the statements. You will progress from screen to screen using your voice. To advance, say &quot;next.&quot; When you get to the true/false statements, give your answer, &quot;true&quot; or &quot;false&quot;. After you have answered, the next question will appear on the screen. When you have answered all the questions for that diagram, a screen will appear telling you that. When you are ready, say “next” to see the next description.</td>
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</tr>
<tr>
<td>Let's start with a practice trial. On the next screen, you'll study a diagram of human circulatory system. When you're done studying, you'll advance to the next screen for the first question. There will be 6 questions for this diagram. The experimenter will be outside the room while you go through the practice trial. When you're done, please open the door to call the experimenter back into the room.</td>
<td>Before we begin, please sit on both of your hands. Please remain seated this way for the entirety of the experiment.</td>
</tr>
<tr>
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</tr>
<tr>
<td>[Insert practice diagram / statements]</td>
<td>[Insert practice diagram / statements]</td>
</tr>
</tbody>
</table>
Practice Trial Complete!

You have now completed the practice text. Please open the door to call the experimenter back into the room.

<table>
<thead>
<tr>
<th>Practice Trial Complete!</th>
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</tr>
</tbody>
</table>

The next diagram will be the map of a small town. As before, you will have as much time as you need to learn the diagram. When you are finished studying and ready to evaluate statements about the map, say “next.” Evaluate each statement as either “true” or false.”

<table>
<thead>
<tr>
<th>The next diagram will be the map of a small town. As before, you will have as much time as you need to learn the diagram. When you are finished studying and ready to evaluate statements about the map, say “next.” Evaluate each statement as either “true” or false.”</th>
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</tr>
</tbody>
</table>

The next diagram will be the layout of a convention center. You will have as much time as you need to learn the diagram. When you are finished studying and ready to evaluate statements about the layout, say “next.” Evaluate each statement as either “true” or false.”

<table>
<thead>
<tr>
<th>The next diagram will be the layout of a convention center. You will have as much time as you need to learn the diagram. When you are finished studying and ready to evaluate statements about the layout, say “next.” Evaluate each statement as either “true” or false.”</th>
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</tbody>
</table>

The next will be the diagram of a bicycle pump. You will have as much time as you need to learn the diagram. When you have finished studying the diagram, say “next” to see the questions. Evaluate each statement as either “true” or false.”

<table>
<thead>
<tr>
<th>The next will be the diagram of a bicycle pump. You will have as much time as you need to learn the diagram. When you have finished studying the diagram, say “next” to see the questions. Evaluate each statement as either “true” or false.”</th>
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<td>Before we begin, please sit on both of your hands. Please remain seated this way for the entirety of the experiment.</td>
</tr>
</tbody>
</table>

The next will be the diagram of a car brake. You will have as much time as you need to learn the diagram. When you have finished studying the diagram, say “next” to see the questions. Evaluate each statement as either “true” or false.”

<table>
<thead>
<tr>
<th>The next will be the diagram of a car brake. You will have as much time as you need to learn the diagram. When you have finished studying the diagram, say “next” to see the questions. Evaluate each statement as either “true” or false.”</th>
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You have now completed this part of the experiment. Please open the door and call the

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| experimenter back into the room. Thank you for your participation! | experimenter back into the room. Thank you for your participation! |
APPENDIX E

Practice Text

Amusement park
Americana World is a large amusement park based on US history and geography. It has a large parking lot leading to Revolution Path. You go west on Revolution Path and you will find the ticket booth on your right decorated with US flags. Past the ticket booth, you turn right on Arctic Highway. (53)

Statements

1 route verbatim
You go west on Revolution Path and you will find the ticket booth on your right decorated with US flags. (T)

1 route inference
Coming back from Arctic way, you turn left on Revolution Path and you will find the ticket booth on your right. (F)

1 survey verbatim
West of the ticket booth, the Arctic Highway goes south from Revolution Path. (F)

1 survey inference
The parking lot is east of the ticket booth. (T)
Practice Diagram True/False Statements

- The systematic circuit delivers oxygenated blood around the body. (T)
- The pulmonary circulation carries blood to the lungs. (T)
- The oxygenated blood flows back to the heart through aorta. (F)
- The renal artery takes blue blood away from kidneys. (F)
- The aorta divides into smaller arteries to deliver oxygenated blood in the body. (T)
- Blood flows back to the heart from head and arms via inferior vena cava. (F)
Environment: Town

Text Description

North of town are the White Mountains and west of town is the White River, which flows south from the White Mountains. The main road by town runs in the east-west directions and crosses the White River. The stables are on the south side of this road, named River Highway, and across the road to the north is the town. Running up through the town from River Highway to the White Mountains is Mountain Rd. The gas station is on the west side of Mountain Rd. and the north side of River Highway, at the intersection, and the restaurant is just across Mountain Rd. from the gas station. The town hall is on the east side of Mountain Rd. a little farther along, and the Maple St. circle is on the west side of Mountain Rd. across from the town hall in the middle of the circle created by Maple St. and Mountain Rd. is a park with a gazebo. On the west side of the circle facing onto Maple St. is the school and on the north is the store.

Diagram Description
**Town True/False Statements**

**Inference Route**

From your position with the Town Hall on your left, the White Mountains are behind you. (T)
Driving toward Mountain Rd. on Maple St., the School is behind you. (T)
Driving from the Town Hall to the Gas Station, you pass Maple St on your right. (T)
Driving toward the White Mountains on Mountain Rd., the Gas Station and the Town Hall will both be on your right. (F)
Coming from the White Mountains on Mountain Rd., you turn left to reach the Store. (F)
Driving toward Mountain Rd. from the Store, you see, on your left, the Gazebo. (F)
The White River runs north-south along the western border of this region. (T)
Mountain Rd. connects the River Highway to the mountains along the eastern border. (T)
Maple St. runs along the southern border of the park. (T)
The Town Hall is across the street from the east side of the park. (T)

**Inference Survey**

The closest building to the White River is the School. (T)
The Gas Station is east of the river and south of Maple St. (T)
Directly across the Mountain Rd. from the Gazebo is the Town Hall. (T)
The School is on a road that runs east-west. (F)
On the west side of Mountain Rd. is the Town Hall. (F)
Directly across the park from the School is the Gas Station. (F)
Drive east along the River Highway to where the highway crosses the White River to reach Etna. (T)
You are forced to make a right turn after you travel a block on Maple St. (T)
You leave the town of Etna by taking the River Highway after turning left from Mountain Rd. (T)
The School is on your left, about a half a block after you turn off of Maple St. (T)
Environment: Convention Center

Text Description

You enter from the southeast corner of the building. As you come in, turn right. To your right will be the “personal computers” room. Continue until you’re forced to make a left. The “Stereo components” room will be in front of you as you turn left. Now you’re facing west. To your left as you walk down the hall will be (first) the “VCR’s” room and then the “televisions” room. To your right, you’ll pass the “CD’s” room. At the end of this hall you’ll see the cafeteria. Here you’ll have to turn left again. You’ll pass the door to the cafeteria on your right, but no doors to your left. After the cafeteria, you’ll pass the restrooms. The office is at the end of this hall. Turn left once more. There will be doors to your left again, as in the second hall. The first one leads to the “35mm cameras” room, the second to the “movie cameras” room. To your right, you’ll pass a bulletin board. At the end of the hall, you’ll find a water fountain to your right, and the entrance/exit door once more.

Diagrammatic Description

Convention Center True/False Statements

Route
- Looking into the Movie Camera Display, the Bulletin Board is behind you. (T)
- Walking from the Personal Computers to the Televisions, you pass, on your right, the Stereo Components. (T)
- Looking into the VCR display, the Cafeteria is to your right. (T)
- Walking from the Stereo Components to the CD's, you pass, on your right, the 35mm Cameras. (F)
- Walking from the Restrooms to the entrance, you pass, on your right, the CD Players. (F)
- Looking into the Cafeteria, the Office is to your left. (F)
- As you walk into the building, you see, on your left, a Bulletin Board. (T)
- You walk past the Televisions, on your right, and continue forward until you see, again on your right, the VCR's. (T)
- Walking past the Movie Cameras on your right, you see, again on your right, the 35mm Cameras. (T)
- Continuing straight ahead from the entrance, where the Bulletin Board is on your left, you reach, on your right, the Movie Cameras. (T)

Survey
- The VCR's are north of the Movie Cameras and east of the Televisions. (T)
- Directly east of the Cafeteria are the CD Players. (T)
- The Cafeteria is northwest of the entrance and north of the Restrooms. (T)
- South of the 35mm Cameras are the Televisions. (F)
- Directly south of the Office are the Restrooms. (F)
- The Personal Computers are west of the Cafeteria and south of the entrance. (F)
- Along the north wall, directly west of the Personal Computers are the Stereo Components. (T)
- Directly south of the Cafeteria, on the west wall, are the Restrooms. (T)
- In the northwest corner of the center section, with the entrance facing north, are the Televisions. (T)
- East of the Bulletin Board, on the east side of the building near the southeast corner, is the entrance. (T)
Mechanical System: Bike Pump

Text Description

**Structural Description:** The bicycle pump is a tall cylinder with a handle extending from the top that can move up and down. Attached to the bottom of the handle in the middle of the cylinder is the piston. Next to the piston is the inlet valve that can open and close. Below the inlet valve is the chamber. Extending outward from the chamber at the bottom is the outlet hose. Between the chamber and the hose is the outlet valve, which can open and close.

**Functional Description:** When the handle is pulled up, it pulls the piston up. The pressure of the upward movement of the piston causes the inlet valve next to the piston at the top of the chamber to open and the outlet valve at the bottom of the chamber of the pump to close. This allows air to enter the lower chamber. When the handle is pushed down, pressure is exerted in the chamber causing the outlet valve to open. The pressure in the chamber and the opening of the outlet valve causes air to exit through the hose.

**Diagrammatic Description**

Bike Pump True/False Statements

- The piston is attached to the wall of the cylinder.
- The inlet valve is open when the outlet valve is closed.
- The piston is at the bottom of the handle.

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- The inlet valve opens when the handle is pulled up.
- The outlet valve extends outward from the piston.
- Pulling the handle up pulls the inlet valve up.
- Pushing the handle down closes the inlet valve.
- Pressure build up in the chamber opens the outlet valve.
- The downward movement of the piston causes the inlet valve to close.
- The outlet valve opens when the piston is raised.
- The outlet valve allows air to enter the chamber.
- The pump works when the outlet valve stays open.
- Next to the handle is the inlet valve.
- Next to the hose is the outlet valve.
- The outlet valve is between the chamber and the hose.
- The inlet valve is above the chamber.
Mechanical System: Car Brake

Text Description

**Structural Description:** The brake or brake drum is a circular structure. Directly inside the sides of the brake drum are two thick semicircular structures called the brake shoes. The brake fluid reservoir is located above and to the side of the brake drum. From the brake fluid reservoir, a tube runs down sideways and then down to the middle of the brake drum. Extending from both sides of the tube in the middle of the brake drum are wheel cylinders surrounding small pistons. Brake fluid can move from the reservoir through the tube to the pistons. The small pistons can move outward toward the brake shoes. The brake shoes can move outward toward the brake drum.

**Functional Description:** From the brake fluid reservoir, brake fluid enters and travels sideways and down the tube. As the brake fluid accumulates at the bottom of the tube, pressure is exerted on the small pistons inside the wheel cylinders. This causes the pistons to push outward toward the brake drum. The outward movement of the shoes causes friction along the inside of the brake drum, slowing the rotation of the wheel.

Diagrammatic Description

![Car Brake Diagram](image)

**Car Brake True/False Statements**

- Brake fluid can move to the brake shoe.
- The brake drum moves towards the brake shoe.
- The brake fluid reservoir is inside the brake drum.
- The wheel cylinders surround the small pistons.
- The small pistons are adjacent to the brake shoes.
- The pressure of fluid accumulation is exerted on the small pistons.
- The tube is next to the wheel cylinder.
- The wheel cylinders are next to the tube.
- Brake fluid pushes the brake drum outward.
- The brake shoes are circular devices.
- Next to the brake drum are the wheel cylinders.
- The tube penetrates the brake shoes.
- The pistons put pressure on the brake shoes.
- The brake fluid stays in the tube.
- The amount of brake fluid released determines time to brake.
- The upward movement of the brake shoe slows the rotation of the wheel.
APPENDIX F

Study 2 Questionnaire

Post Questionnaire

Section 1 (to be filled by the experimenter)

Participant ID: [fill-in]
Date: [pop-out calendar]
Condition:
  • 01 (GP)
  • 02 (GA)

Section 2 (to be filled by the participant)

Gender: [fill-in]
Age: [drop down menu of birth year]
What is your dominant hand?
  • Right
  • Left
  • Ambidextrous
Are you bilingual (conversational proficiency)?
  • Yes
  • No
Please rate the difficulty of the Town you studied:
Very easy 1 2 3 4 Very difficult
Please describe the strategies you used to understand and remember the Town.
[open response]

Please rate the difficulty of the Convention Center you studied:
Very easy 1 2 3 4 Very difficult
Please describe the strategies you used to understand and remember the Convention Center.
[open response]

Please rate the difficulty of the Bike Pump you studied:
Very easy 1 2 3 4 Very difficult
Please describe the strategies you used to understand and remember the Bike Pump.
[open response]

Please rate the difficulty of the Car Brake you studied:
Very easy 1 2 3 4 Very difficult
Please describe the strategies you used to understand and remember the Car Brake.

[open response]

<table>
<thead>
<tr>
<th>Section 3 (GP condition)</th>
<th>Section 3 (GA condition)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sitting on hands made it harder to understand and remember text descriptions.</td>
<td>Gesturing helps understanding or remembering text descriptions.</td>
</tr>
<tr>
<td>Strongly disagree 1 2 3 4 Strongly agree</td>
<td>Strongly disagree 1 2 3 4 Strongly agree</td>
</tr>
<tr>
<td>Sitting on hands made it harder to understand and remember map/diagram.</td>
<td>Gesturing helps understanding or remembering map/diagram.</td>
</tr>
<tr>
<td>Strongly disagree 1 2 3 4 Strongly agree</td>
<td>Strongly disagree 1 2 3 4 Strongly agree</td>
</tr>
<tr>
<td>Did sitting on hands interfere with studying the text descriptions? If so, how?</td>
<td>Did you find yourself gesturing? If so, please describe and explain the intention of your gestures.</td>
</tr>
<tr>
<td>[open response]</td>
<td></td>
</tr>
<tr>
<td>Did sitting on hands interfere with studying the map/diagram? If so, how?</td>
<td></td>
</tr>
<tr>
<td>[open response]</td>
<td></td>
</tr>
</tbody>
</table>
### APPENDIX G

**Gesture Coding Scheme**

<table>
<thead>
<tr>
<th>Category</th>
<th>Sub-category</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Type</strong></td>
<td>Representational</td>
<td>General: Participant gestures to visualize the content of the texts of diagrams.</td>
<td>0 = not observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 = observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pointing &amp; Tracing: Participant uses finger or hand to point and trace along the <strong>diagram</strong> to process information. Hands should be in the air and close to the screen. Gesture trajectory is on a plain that is parallel to the screen.</td>
<td>0 = not observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 = observed</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Air</td>
<td>The gesture is performed in the air.</td>
<td>0 = not observed</td>
</tr>
<tr>
<td></td>
<td>Surface</td>
<td>The gesture is performed on a surface (desk / leg).</td>
<td>0 = not observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 = observed</td>
</tr>
<tr>
<td></td>
<td>Hand</td>
<td>The gesture is performed on one hand by the other hand.</td>
<td>0 = not observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 = observed</td>
</tr>
<tr>
<td><strong>Hand</strong></td>
<td>Left</td>
<td>Left hand is used in the gesture.</td>
<td>0 = not observed</td>
</tr>
<tr>
<td></td>
<td>Right</td>
<td>Right hand is used in the gesture.</td>
<td>0 = not observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 = observed</td>
</tr>
<tr>
<td><strong>Symmetry</strong></td>
<td>N/A</td>
<td>The gesture is symmetric.</td>
<td>0 = not observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1 = observed</td>
</tr>
<tr>
<td><strong>Looking at</strong></td>
<td>N/A</td>
<td>Participant was looking at their hands when performing a gesture.</td>
<td>0 = not observed</td>
</tr>
<tr>
<td><strong>Hand</strong></td>
<td></td>
<td></td>
<td>1 = observed</td>
</tr>
<tr>
<td><strong>Time</strong></td>
<td>Study Time</td>
<td>In seconds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Test Time</td>
<td>In seconds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gesture Time at Study</td>
<td>In seconds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gesture Time at Test</td>
<td>In seconds</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**

**Gesture Separation Rules**

Stop counting time if hands don't move for 3 seconds after a representational/beat gesture.