Characterizing representational gestures in collaborative sense-making of vectors in introductory physics

Stacy M. Scheuneman and Virginia J. Flood
Department of Learning and Instruction, University at Buffalo, Buffalo, NY, USA

Benedikt W. Harrer
Department of Physics, University at Buffalo, Buffalo, NY, USA

An understanding of vectors and vector operations is crucial for success in physics, as this serves as the foundation for various essential concepts, including motion and forces. Previous research indicates that only a fraction of introductory physics students have a usable knowledge of vectors and vector operations, and that more attention should be given to how students make sense of vectors. We examined classroom video data from an introductory physics course wherein students worked collaboratively through learning activities to introduce vectors and vector operations. During these activities, students' employment of gesture as a representational mode facilitated group sense-making. We propose a preliminary taxonomy of gestures for representing vector magnitudes, directions, and initial and terminal points. By identifying and characterizing the gestures used by students, we can gain insights into their learning processes and conceptual understanding of vectors, which can inform instructional design and teaching practices.

2023 PERC Proceedings edited by Jones, Ryan, and Pawl; Peer-reviewed, doi.org/10.1119/perc.2023.pr.Scheuneman

I. VECTORS, GESTURES, AND SPATIAL THINKING

Prior research on introductory physics students' vector knowledge indicates that the traditional treatment of vectors and their operations is insufficient. Using the results from administration of the Vector Knowledge Test, Knight determined that only 50 percent of students in a calculus-based first semester physics course demonstrated the ability to perform vector addition [1]. Furthermore, many introductory physics students have difficulties in carrying out vector addition and subtraction, even after the completion of a first semester mechanics course. For example, on a graphical vector assessment administered in a second semester, algebra-based introductory physics course, 73 percent of students answered a one-dimensional addition problem correctly, 44 percent answered a two-dimensional addition problem correctly, and 35 percent answered a two-dimensional subtraction problem correctly [2]. Similar findings saw about 50 percent of students able to correctly answer a vector addition problem after a semester of traditional instruction [3].

The findings from an investigation of arrow and algebraic vector notation suggests that while students who are given an algebraic notation assessment of vector addition achieved higher scores, students given an arrow notation assessment answered with solution methods requiring qualitative component canceling and angle reasoning at a higher rate [4]. This may indicate that the arrow notation presents students with a greater challenge due to subtleties in the representation of spatial characteristics such as direction and magnitude. Although arriving at the correct numerical answer is an important goal for physics students and their instructors, developing a conceptual understanding of problems and their solutions is arguably of greater importance. Doing so requires that students are provided opportunities to take advantage of different representational modes, including gestural modes.

Gestures are physical movements that people make using their hands and arms which are meaningful substitutions for ideas and entities. In addition to playing a significant role in communication, there is a growing body of evidence that indicates that gestures affect thinking and learning [5]. The evidence is especially strong for domains in which spatial reasoning is an essential competency, such as the natural sciences and mathematics [6] [7] [8].

Representational gestures are gestures which are visually similar to what they reference. Representational gestures can be further categorized as iconic gestures, which resemble the shape of what is being gestured about, or abstract deictic gestures, in which an empty space in front of the body is pointed to and treated as being occupied by some imaginary entity [9].

Gestures' ability to convey spatial information has been established as a productive tool in geometric reasoning and graphing of mathematical functions [10] [11]. Due to the highly spatial nature of vectors and vector operations, students' use of gestures during sense-making activities which are focused on developing these foundational skills should be of particular interest to introductory physics educators.

Both the form of gesture and the nature of vector properties are considered in the characterization of vector gestures. The four main forms of representational gestures are:

- imitation, in which the hands are used to mime actions associated with an object
- portrayal, in which the hands are used to represent an object's form
- drawing, in which the hands are used to trace or outline a shape
- sculpting, in which the hands are used to mold or carve a shape [12].

The use of dynamic gestures - those which represent change - has also been linked with increased success in mathematics proof development [13]. The nature of vector properties is classified using a schema for organizing spatial skills. This schema considers whether the referenced properties are intrinsic or extrinsic, as well as whether they are dynamic (changing) or static (unchanging) [14]. Intrinsic properties are the spatial features of an object, such as the shape and size. For vectors, the magnitude is an intrinsic property. Extrinsic properties are the locating features of an object, in relation to other objects or to a frame of reference. For vectors, the direction and the initial and terminal points are extrinsic properties.

Despite the difficulties students have with vectors and our knowledge that gestures play an important role in students' spatial reasoning in STEM, we know surprisingly little about how students use gestures to make sense of and reason together about vectors. The purpose of this qualitative study is to investigate how students gesture about vectors, and how these gestures convey students' understanding of various vector properties. The goal of this paper is to characterize how students use gesture to make sense of vectors. We discuss the affordances and limitations of these different types of gestures for understanding and reasoning about vectors. Students were observed during collaborative problem solving and sense-making activities while working through learning activities to introduce vectors and vector operations in two dimensions. As part of a larger project to examine physics students' use of dialogic gesture in sense-making, we propose a preliminary taxonomy of gesture characteristics for representing vector properties, accounting for static and dynamic representations of vector magnitudes, directions, and initial and terminal points.

II. METHODOLOGY

In this qualitative study, a microethnographic approach [15] was used to analyze the gestures of undergraduate physics students. A microethnographic approach allows us to reveal and document unfolding processes of sense making instead of just examining outcomes at fixed points in time. The primary data source is a video corpus of an algebra-based introductory undergraduate physics course using the Collaborative Learning through Active Sense-Making in Physics

FIG. 1. Two students simultaneously portray the heads of two force vectors acting on the same object in opposite directions.

(CLASP) curriculum [16]. Specific segments analyzed in this study were recordings of three different groups working on three connected activities on vector properties and operations. For each group, 30 minutes of video were analyzed.

In the first activity, students were tasked with determining the range of possible values for two masses when combined, and for two forces when combined, to contrast the differences involved in adding scalar quantities and adding vector quantities. In the second activity, students determined a method for adding vectors tip to tail, first using two vertical force vectors of different magnitudes with the same direction; then extended this method to two vertical force vectors of different magnitudes acting in opposite directions and two force vectors of different magnitude acting perpendicular (one vertical and one horizontal) to one another. In the third activity, students performed a graphical vector subtraction for two diagonal position vectors to find the displacement. Work took place in groups of three to four students. Students were seated together and were directed to show their work on a large whiteboard.

In identifying and characterizing gestures, gestures were grouped together by the form of the gesture (imitation, portrayal, drawing, and sculpting), and the intrinsic/extrinsic and static/dynamic nature is considered for the referent vector properties of direction/orientation, magnitude, and initial and terminal points.

Four classes of representational gestures were identified in this analysis, and specific cases of each are analyzed: portraying, drawing, sculpting, and imitating handling of the vector.

We present our characterization of these different types of gesture in detail to allow the reader to judge the suitability of our categories for describing students' use of gesture. The first author watched each example repeatedly to establish reliability and accuracy of each characterization. In future work, we plan to test the reliability of these categories using independent coders to measure inter-rater reliability.

III. CHARACTERIZING GESTURES ABOUT VECTORS DURING SENSE-MAKING

During the sense-making activities at the focus of this study, students were observed gesturing about intrinsic and extrinsic properties of the vector which were still being made sense of using dynamic gestures. Conversely, students tended to gesture about characteristics using static gestures when they were more certain (although not necessarily correct) in their understanding.

A. Portraying the vector

One class of gestures for vectors observed is use of the hands to portray the vector. While portraying the vector, the hands are angled at the wrist and the fingers are extended in line with the flattened palm. For example, for the gestures shown in Fig. 1, students portray the heads of two oppositely facing vectors head-to-head. In this gesture, we see static representation of the vectors' direction and terminal points, as well as the spatial relationship between the two vectors.

Some information about the vectors may be missing from this gesture. It is unclear whether information about the initial points and magnitude is conveyed, since the portrayal of the vectors using the hands is limited by the hands' symmetry. The student on the left, however, has their lower hand angled straight with their forearm, which may suggest that static information about the initial points and magnitudes is being conveyed. During the activity in which these gestures take place, students are attempting to add two oppositely pointing vectors, with the vector of greater magnitude pointing up.

B. Drawing the vector

Students drew hypothetical vectors by tracing a line by moving an extended finger linearly back and forth between two points, such as shown in Fig. 2. The magnitude and initial and terminal points are represented statically. The static nature of the initial and terminal points in the gesture can be seen as the tracing never passes the boundary of either point. The representation of the direction of the hypothetical vector is dynamic, indicated by the switching of directions of the stroke at least once. Although similar to gestures that portrayed the vector, with these drawing gestures, speakers did not commit to one direction.

These drawing gestures helped the speaker convey information about the orientation and placement of the vector without specifying direction. Often, this occurred when the direction of the resultant vector had not yet been determined by the speaker.

For example, following the gesture made by the student in Fig. 2, another member of the group draws a dashed line without an arrowhead, then asks for clarification of which direction the vector should be pointing multiple times. In re-

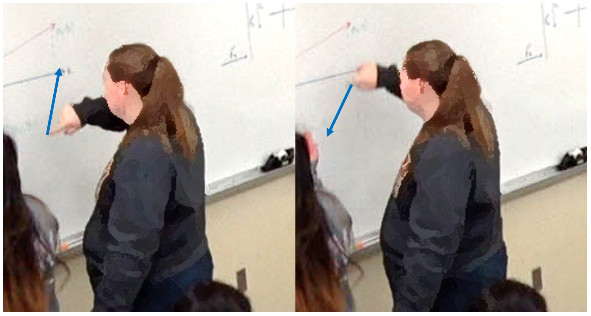

FIG. 2. A student traces a hypothetical vector during the graphical vector subtraction activity, in which students need to determine a method for finding the displacement vector from two position vectors.

sponse, the gesturing student does not respond by stating a direction but refers back to the reference materials and says they should write out an equation.

C. Sculpting the vector

The two previously described gestures can be combined to convey additional information, in which the speaker sculpts around a vector with a moving, flattened hand, such as that seen in Fig. 3. Like gestures which draw the vector, the direction is represented dynamically while the magnitude and initial and terminal points are represented statically. There is a subtle difference with the addition of the portrayal of the vector as well, with the pointed fingers changing direction and the speaker specifically questioning the direction.

In the activity shown in Fig. 3, students in the group are discussing whether subtraction of the one vector (the subtrahend) from another (the minuend) would require arranging the subtrahend in the same direction as the minuend (shown in the top panels of the figure) or in the opposing direction (shown in the bottom panels of the figure).

D. Imitating handling the vector

When students used gestures to imitate actions done to vectors, they held it as though it were a physical object taking up space in their hands. By rotating or translating the invisible vector while holding the ends of the imaginary vector, which is done with either the fingers of two hands or two fingers on the same hand, or gripping the vector along the middle, the speaker conveys information about extrinsic characteristics of the vector.

When simulating a rotation of the vector, such as in the gesture shown in Fig. 4 (left), the magnitude and initial point are represented statically, with the distance between the hands remaining the same and the left hand remaining in place. Direction and the terminal point are represented dynamically, as seen in the changing position of the right hand. After this gesture, they direct the other member of the group to draw a vector which only shows a reflection over the y-axis, as opposed to the complete 180 degree rotation represented in the gesture. This suggests that although the gesture represents what should be done to the vector, the speaker may be uncertain.

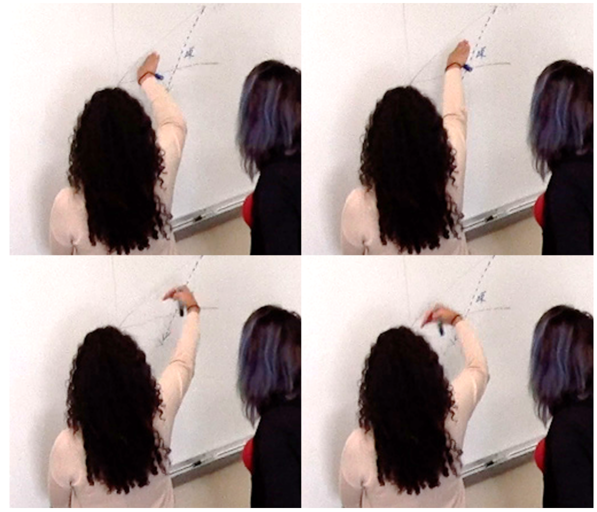

FIG. 3. Student sculpts around a vector with their fingertips pointing in the direction of the motion of the hand.

When transforming a vector via translation, such as in the gesture shown in Fig. 4 (right), students simulate holding on to the ends of the vector and sliding it across the diagram. In this type of gesture, the magnitude and direction of the vector are represented statically, while the initial and terminal points are represented dynamically.

In this interaction, the speaker was trying to convince their group member that the direction and magnitude were drawn incorrectly in the diagram by showing that the magnitude did not match the distance between their hands and that the direction didn't change when they had already agreed that it should be the opposite. After the gesture, the group member erases the additional dashed lines at the end of the vector and changes the direction and placement of the arrowhead.

IV. DISCUSSION

Across the examples of gestures about vectors described in this preliminary analysis, dynamic representations of vector properties accompanied students' active reasoning with the vector property. For example, when direction was being represented dynamically in a gesture, the speaker was often grappling with figuring out the vector's direction. Conversely, static representations were accompanied with a lack of active reasoning - for example, speakers who gestured using static representations of direction were not focused on determining direction.

Few students observed appeared to have difficulty in under-

FIG. 4. Student holds the vector by either end while simulating a rotation (left) and a translation (right), both done by maintaining the distance between their hands and changing their position relative to the whiteboard.

standing the magnitude of vectors, and no dynamic representations of magnitude were observed in this initial exploration of the data. This lines up with the previously mentioned literature on vector understanding of introductory physics students, which shows that many students have an adequate understanding and ability to determine the magnitudes of vectors but struggle with determining their direction.

In the first activity, although many students were able to distinguish between adding scalar quantities and adding vector quantities, student initiated consideration of differing directions beyond parallel and perpendicular combinations of vectors was not observed. This may indicate that many students possess only a rudimentary understanding of vectors having direction when coming into introductory physics.

Similarly, difficulty with managing vectors with different directions was observed in the second activity. Although students were able to add two parallel vectors with the same direction with ease, and decide that a tip-to-tail method was required to do so, students were not able to subsequently apply this method to two parallel vectors with opposite direction and the two perpendicular vectors without struggling with an attempt to add vectors using a tip-to-tip representation.

Gestures representing direction and initial and terminal positions dynamically were commonly seen in the third activity, which coincided with students having greater difficulty in determining the placement and direction of vectors during the graphical vector subtraction.

V. CONCLUSIONS AND FUTURE RESEARCH

By analyzing a small subset of the large corpus of video data in this exploratory study, we were able to identify trends in students' gestures about vectors, which provided valuable insights into their understanding of vector properties. We observed that students who dynamically gestured about certain vector properties were often in the process of making sense and developing understanding about how those properties were at play in the context of the activity. Conversely, vector properties which were represented statically in gestures tended to be those which did not require as much attention from students.

While these findings provide only an initial look into the relationship between students' gestures and the evolution of their understanding of vector properties, they open up several avenues for future research. The next step in furthering our understanding of this relationship is to conduct a larger-scale analysis of video data, encompassing a broader range of students, modes of communication and representation, and physics learning contexts, including activities farther in the curriculum which require more challenging applications of vectors.

The limitations of this study include its small sample size and that it provides a close analysis over a short period of time and therefore cannot shed light longitudinally on how students use gestures to think about vectors and how this may impact learning over time. However, this study present first steps for a more comprehensive analysis. Future work could examine how students' use of gesture changes over time as they learn about vectors and also could look for patterns in larger samples of students.

In conclusion, this exploratory study has established a foundation for understanding the role of gestures in students' comprehension of vector properties. Our initial observations highlight the potential of gestures as indicators of active sense-making and provide a basis for future research. By expanding the range and depth of investigation, we can deepen our understanding of how gestures can effectively support both the development of vector-related knowledge and skills, as well as sense-making and problem-solving practices in the wider domain of physics.

ACKNOWLEDGMENTS

This work is supported by NSF ECR-EHR Core Research Award No. 2201821 DiGEST Physics: Dialogic gesture in collaborative sense making in physics.

[1] R. D. Knight, The vector knowledge of beginning physics students, The Physics Teacher **33**, 74 (1995).
[2] N. L. Nguyen and D. E. Meltzer, Initial understanding of vector concepts among students in introductory physics courses, American Journal of Physics **71**, 630 (2003).
[3] S. Flores, S. E. Kanim, and C. H. Kautz, Student use of vectors in introductory mechanics, American Journal of Physics **72**, 460 (2004).
[4] A. F. Heckler and T. M. Scaife, Adding and subtracting vectors: The problem with the arrow representation, Physical Review Special Topics-Physics Education Research **11**, 010101 (2015).
[5] M. A. Novack and S. Goldin-Meadow, Gesture as representational action: A paper about function, Psychonomic Bulletin and Review **24**, 652 (2017).
[6] R. E. Scherr, Gesture analysis for physics education researchers, Physical Review Special Topics-Physics Education Research **4**, 010101 (2008).
[7] M. W. Alibali, M. J. Nathan, M. S. Wolfgram, R. B. Church, S. A. Jacobs, C. J. Martinez, and E. J. Knuth, How teachers link ideas in mathematics instruction using speech and gesture: A corpus analysis, Cognition and Instruction **32**, 65 (2014).
[8] V. J. Flood, F. G. Amar, R. Nemirovsky, B. W. Harrer, M. R. Bruce, and M. C. Wittmann, Paying attention to gesture when students talk chemistry: Interactional resources for responsive teaching, Journal of Chemical Education **92**, 11 (2015).
[9] S. Kita, How representational gestures help speaking, Language and Gesture **1**, 162 (2000).
[10] M. J. Nathan and C. Walkington, Grounded and embodied mathematical cognition: Promoting mathematical insight and proof using action and language, Cognitive Research: Principles and Implications **2**, 1 (2017).
[11] S. Gerofsky, Seeing the graph vs. being the graph, in *Integrating Gestures*, edited by G. Stam and M. Ishino (John Benjamins, 2011) Chap. 18, pp. 254–265.
[12] I. Masson-Carro, M. Goudbeek, and E. Krahmer, Can you handle this? the impact of object affordances on how co-speech gestures are produced, Language, Cognition and Neuroscience **31**, 430 (2016).
[13] E. L. Pier, C. Walkington, V. Clinton, R. Boncoddo, C. Williams-Pierce, M. W. Alibali, and M. J. Nathan, Embodied truths: How dynamic gestures and speech contribute to mathematical proof practices, Contemporary Educational Psychology **58**, 44 (2019).
[14] N. S. Newcombe and T. F. Shipley, Thinking about spatial thinking: New typology, new assessments, in *Studying Visual and Spatial Reasoning for Design Creativity* (Springer, 2014) pp. 179–192.
[15] R. Y. Bayeck, Is microethnography an ethnographic case study? and/or a mini-ethnographic case study? an analysis of the literature, International Journal of Qualitative Methods **22**, 16094 (2023).
[16] W. Potter, D. Webb, C. Paul, E. West, M. Bowen, B. Weiss, L. Coleman, and C. D. Leone, Sixteen years of collaborative learning through active sense-making in physics (clasp) at uc davis, American Journal of Physics **82**, 153 (2014).