

The role of gestures in teaching and learning anatomy and physiology

Stephanie Wallace ^{1*} , Hayat Hokayem ¹ 

¹Texas Christian University, Fort Worth, TX, USA

*Corresponding Author: stephanie.wallace@tcu.edu

Citation: Wallace, S., & Hokayem, H. (2026). The role of gestures in teaching and learning anatomy and physiology. *Eurasian Journal of Science and Environmental Education*, 6(1), 43-49. <https://doi.org/10.30935/ejsee/18439>

ABSTRACT

Anatomy and physiology is an undergraduate science course with a reputation of being a “gatekeeping” course because students must achieve a grade of C or better to continue with coursework in the student’s chosen STEM major, which many students fail to accomplish. The volume of material and complexity of the content are two reasons why the course is difficult for students to master and nationally has a high drop/fail/withdraw rate. This study examines the role of gestures in teaching and learning in an undergraduate anatomy and physiology course and asks these research questions: (1) Do pointing gestures by students affect student outcomes more than pointing gestures by the teacher alone? and (2) Do representational gestures by students affect student outcomes? We found that representational gestures helped students learn cranial nerve content better compared to students who did not use gestures as measured by exam scores. Additionally, after a unit incorporating gestures in teaching and learning, students indicated that they would be more likely to use their hands to study and learn in the future.

Keywords: gestures, learning, embodiment, science education, physiology

Received: 24 Nov. 2025 ♦ Accepted: 15 Apr. 2026

INTRODUCTION

Some undergraduate science courses have the reputation of being “gatekeeping” or “weed out” courses because students must achieve a grade of C or better to continue with coursework in the student’s chosen STEM major (Lunsford & Diviney, 2020). One such course is anatomy and physiology for nursing and kinesiology students. The volume of material and complexity of the content are two reasons why the course is difficult for students to master and nationally has a 30-50% drop/fail/withdraw rate (Lunsford & Diviney, 2020; Marwaha et al., 2021).

Anatomy is the structure of a molecule, cell, tissue, or organ, and physiology is the function of that structure. A major aspect of learning anatomy and physiology is identifying how the structure of that body part relates directly to its function, and how a pathology can develop if the structure changes, thereby altering the function of that body part. Sometimes there are multiple aspects or functions of a tissue or organ, and students must keep them straight and apply them properly to different scenarios. For example, different types of tissue lines are the respiratory

tract in different areas. However, smoking causes metaplasia, a transformation of one tissue to a different type. Students must understand and apply how changing the structure of the tissue will change its function.

This study focused on the anatomy and physiology of spinal tracts and cranial nerves and students’ abilities to remember and apply that knowledge. Spinal tracts and cranial nerves are different types of information pathways used to transmit information to and from the brain (Augustine, 2017). Each spinal tract or cranial nerve carries a slightly different type of information and is located in a different area of the body. They carry major clinical significance for future nurses (Martínez-Marcos & Sañudo, 2019).

Nursing students must learn to apply this information to be successful in future coursework and in their careers, but students struggle in this foundational course. Gestures are commonly used by teachers and students when teaching and learning, and we know gestures are tied to cognition (Roth, 2001). We also know gestures help with expressing ideas and demonstrate that knowledge is embodied (Alibali & Nathan, 2012), but there are few studies about gestures in science education. This study examines the role of gestures in teaching and learning of spinal tracts and cranial nerves

in an undergraduate anatomy and physiology course and asks these research questions:

1. Do pointing gestures by students affect student outcomes more than pointing gestures by the teacher alone?
2. Do representational gestures by students affect student outcomes?

LITERATURE REVIEW AND CONCEPTUAL FRAMEWORK

Embodied Cognition

Strictly cognitive theories of how learning is accomplished fail to take the body and the environment into consideration. Embodied cognition states that our minds are linked with our bodies' interaction with our environment (Shapiro & Stolz, 2019). Our minds can know by what we do with our bodies. The brain represents what is happening in the world by imagining one's body engaging in the world. Even reading a sentence about kicking a ball will activate motor areas of the brain that are stimulated when you actually kick a ball (Pulvermuller, 2005).

Embodied cognition is concerned with how the mind, body, and environment interact with each other and how our knowledge is grounded in sensorimotor experiences (Barsalou, 2008; Lakoff & Johnson, 1999). By grounding our experiences in the environment, we can exploit features of the environment to reduce cognitive load (Roth, 2001; Shapiro & Stolz, 2019). For example, a baseball player in the outfield is not performing computations about the trajectory of the ball it to catch it 200 feet away. The outfielder instead positions their body directly under the ball as it moves toward them, and the ball's pattern of motion gives him the information required to catch it. The body's state can influence the cognitive state.

Gestures

Gestures are defined as using the arm and/or hand when talking (Goldin-Meadow & Alibali, 2013; McNeill, 1992), and different types of gestures can be created depending on how the arm and hand are used. In this study, we focus on two different kinds of gestures: Pointing (deictic) gestures use the first finger most often to indicate something on a picture or on an object (Alibali & Nathan, 2012; Crowder, 1996; Padalkar & Ramadas, 2011). The purpose of this gesture is to draw attention to the object of conversation. Often this can help clarify exactly what a speaker is referring to by directing attention to the exact place on a diagram or in space they are referring to. Often, the language used to accompany pointing gestures does not make sense in isolation. For example, if someone says, "I will travel there," the word "there" has no meaning without the accompanying pointing gesture visually demonstrating where "there" is. Pointing gestures can also be used to trace a path, indicating trajectory, direction, and/or velocity.

The other major gesture type is a representational gesture, which includes both iconic and metaphoric gestures (Alibali & Nathan, 2012; Hostetter & Alibali, 2008). Both of these types mime the meaning of the word or phrase with the hand or arm. Iconic gestures depict semantic content directly in a miming action, such as when you change the angle of the arm to demonstrate the slope of a line. Metaphoric gestures also mime content but do so indirectly through metaphor. For example, when someone is "holding" an idea and they cup their hands together as if they are holding water. These representational gestures can embellish or enhance what is being verbally communicated or may be redundant to speech (Mathayas et al., 2019; Padalkar & Ramadas, 2011). The person appears to be miming words as they speak or creating an imaginary diagram in the air. Representational gestures can even replace speech altogether (Lim, 2019) or help translate a spatial model to a verbal explanation (Atit et al., 2015). They can act as ephemeral diagrams and may help students externalize explanatory models by making underlying mechanisms more visible (Roth & Welzel, 2001).

Gestures utilize embodied cognition and may decrease cognitive load by grounding information in the environment (Cook & Goldin-Meadow, 2006; Kersting et al., 2023). Gestures decrease the burden on speech production by providing an alternate way to communicate (Cook & Goldin-Meadow, 2006). Gestures may be especially helpful with students who are new to the discipline and struggle with the formal scientific terminology, or for English language learners (Galati & Brennan, 2014; Mathayas et al., 2019; Ünsal et al., 2018). Because gesture has the ability to replace language, it enables students to explain scientific concepts before they fully grasp the proper terminology associated with it (Mathayas et al., 2019; Padalkar & Ramadas, 2011). This is accomplished because the imagery provided by gestures facilitates speech about mental images (Hostetter & Alibali, 2008) as the idea is grounded in the physical environment (Crowder, 1996; Goldin-Meadow, 2011). As students increase their understanding of the concepts, the ability of the student to use appropriate terminology and scientific language increases, and the dependence on gesture to explain decreases. Gesture can then be used simultaneously with speech to accentuate language instead of replacing it, and at this point, the redundant gestures increase comprehension for the speaker and the listener (Goldin-Meadow & Alibali, 2013). While a student is initially learning a concept, their gestures may not match their speech, which foreshadows knowledge change and reflects a readiness to learn. Gesture-speech mismatches are noticed by teachers who can then correct misconceptions and facilitate learning.

A few studies have explored the role of gesture in anatomy and physiology education, but the field could use more empirical studies. The current study aims to build on this research to more specifically place the role of gestures in teaching and learning anatomy and physiology.

METHOD

Participants and Settings

Students were provided an informed consent form to sign before the study began, which was approved by the institutional IRB #2021-176. Students were assigned a randomized student number, and all data were blinded with the randomized student number before any data analysis started. The key containing the student number and the student name was kept in a separate folder. Documents are stored on the institution's secure servers. Students enrolled in these sections were primarily freshmen (63%) and sophomores (30%), and most are nursing majors (73%). Two sections of the same anatomy and physiology course, taught on the same days of the week one hour apart were used for this study. Section A had 57 students enrolled and section B had 44 students. Each section covered the same content and completed the same assessments. Each participant agreed to volunteer for the study according to Institutional Review Board (IRB) protocol approved by Texas Christian University (IRB# 2021-176), and care was taken to ensure students knew that their information would be anonymized and they could withdraw at any time without penalty from this voluntary process. Material targeted for gesture lessons included spinal tracts and cranial nerves, which are historically difficult for students to master.

Spinal Tracts Lesson

Spinal tracts are specific spinal pathways primarily within the spinal cord and brain and are composed of two to three neurons. Each of the neurons has a specific function and a particular place where it travels in the spinal cord and brain. Students must know the anatomy (structure and placement of each neuron) and the physiology (function of each neuron within the pathway) for multiple different spinal tracts. Pointing gestures by the instructor were used to trace the different neurons along the pathways in order, while discussing the function of each. The image used for tracing was from the adopted textbook for the course. For section A, the teacher traced the pathways on a projector version of the illustration, then asked students to do the same with a partner on their paper copy. A printed copy of the textbook image was given to each student because many of them use the e-book version or may not bring their text to class. For section B during the next hour, the instructor again pointed to a projected image of the same textbook illustration on spinal tracts while explaining the function of each neuron. The same printed copy of the image was provided to section B students, but the teacher did not ask these students to point, nor was any voluntary pointing to the image observed.

Cranial Nerves Lesson

Cranial nerves also have important anatomical and physiological importance. They are often used in healthcare settings to test reflexes and general function in the body. Knowing and remembering the specifics of their multiple



Figure 1. A photo demonstrating the gesture used for cranial nerve VI, the abducens nerve (Source: Stephanie Wallace)

functions is difficult for students. For section A, the instructor introduced a representational gesture when explaining each of the twelve cranial nerves to remember the anatomy and/or physiology of that nerve. For example, the trigeminal nerve has three branches that carry sensory information from the face to the brain and its motor function is to assist in coordinating muscles for chewing. The gestures used for this nerve were to use one, two, or three fingers (depending on the specific branch) to trace on the face where the three branches detect sensation, then to tap the underside of the chin to indicate the motion of chewing. For the nerves that control eye movement (cranial nerves III, IV, and VI), the gesture was simply to touch the area of the face where the eye would look toward if that nerve were stimulated (**Figure 1** illustrates the gesture for cranial nerve VI, the abducens nerve).

After going through all nerves, the teacher went through all twelve cranial nerve names, numbers, and gestures twice with section A. Then the students were asked to copy and learn the gestures associated with each cranial nerve. A student requested during class that a video be posted so they could practice and remember at home, and a video was posted by the instructor that evening. 35% of students in section A accessed the video through the learning management system. The video of the gestures made by the teacher for section A was not provided to section B. Section B covered the same content, the same slides were used during discussion of the anatomy and physiology of the cranial nerves, but no representational gestures were used to supplement the lesson. The same amount of total time, one 50-minute class period, was spent on the material in both sections. Time that was spent in section A practicing the gestures was spent instead on discussion and answering student questions in section B. Students asked questions such as "The facial and glossopharyngeal nerves both sense taste, what is the difference between them?"

Exam

Spinal tract and cranial nerve content are tested on an exam with other nervous system information. The exam over the nervous system was given 11 days after the spinal tract lesson and 9 days after the cranial nerves lesson. The exam was created using the university's learning management system to be taken online with a secure browser. Most questions are multiple choice or multi-select ("select all that apply"), and a few are ordering or matching

Table 1. Exam 5 question scores according to question type

Question type	Section A (gestures) average response score	Section B (no gestures) average response score
Cranial nerves	89.00%*	72.07%
Spinal tracts	82.32%	76.61%
Non spinal tract/cranial nerve questions	85.04%	78.84%
All questions	84.91%	78.04%

Note. * $p < 0.05$

questions. When creating the exam, the questions are pooled so that every student receives the same number of questions in a certain content area, but the questions are randomized so students each receive a different selection of questions. Questions are based on learning outcomes given to the students. For this exam there was a pool of spinal tract questions and a pool of cranial nerve questions. The total time to take the exam is timed to estimate an average of one minute per question. While additional questions are added each year to enhance the question pools, most of these exam questions have been in use for over 5 years and have been compared to exam material and questions of other expert teachers to ensure rigor and relevancy.

Example spinal tract question: What types of information are carried along the gracile fasciculus? Select all that apply. Answer choices: arm position, leg position, pain, vibration.

Example cranial nerve question: If a patient has difficulty chewing, where would you look for damage? Answer choices: trigeminal nerve-ophthalmic division, trigeminal nerve-mandibular division, trigeminal nerve-maxillary division, facial nerve, abducens nerve.

Survey and Interviews

After students received their grade results from the exam, students in both sections were asked to complete a Likert survey asking their viewpoints on how spinal tract and cranial nerve content was taught, their confidence in their content knowledge, and how they felt about using their hands to learn. Interviews were semi-structured and asked students' thoughts about what study method was most helpful in learning the content, how long did they used that method, and how much time they spent studying total. The purpose of the survey was to provide additional information about student history of using various types of study methods and perceptions of using gestures that may not otherwise be apparent.

Example interview question: What was the most helpful method you used to learn the spinal tracts? Why do you think it was helpful?

Data Analysis

After the semester ended and final grades were submitted to the registrar, I acquired the exam and survey data and blinded the names. I used descriptive statistics to examine overall exam averages in addition to specific question pools for spinal tracts and cranial nerves. I also ran independent t-tests between the two sections to find if there were differences in overall exam grade as well as

compare performance on the spinal nerves and cranial nerves question pools. This helped to determine if there was a difference in performance between the two sections, or if any differences were more likely due to chance.

Survey results from the 15 students who participated were blinded. Descriptive statistics were used for the Likert questions to determine student thoughts and perceptions on study habits and using gestures. Common themes from free response survey questions and interviews were deduced after coding the short response answers.

RESULTS

Exam

Both section A and section B scored slightly worse on spinal tract questions compared to other nervous system content and the exam average (**Table 1**). Historically, this is a common result since spinal tract information is among the most difficult on this exam. This indicates that pointing gestures by students were not helpful to students on this exam, or the pointing gestures performed solely by the teacher in both sections were sufficient for learning without student copying the instructor gestures. For the cranial nerves content, section A, which used representational gestures to learn, scored significantly better on cranial nerves questions compared to other content questions on the exam ($t_{(18)} = 1.89, p = 0.038$), while section B scored worse on these questions compared to others. These data indicate that representational gestures by the teacher and/or by the students facilitates learning as measured by exam performance. Nervous system content assessed other than cranial nerves and spinal tracts had scores on par with the exam average in both sections.

Survey and Interviews

In the survey, about half of the 14 survey respondents from section A said they had not used their hands to study before taking this class, but 71% said they would do so in the future because gestures help them learn and feel more confident in their knowledge. All survey respondents said they will use their hands to gesture more often in the future when studying. Several participants mentioned using the illustration of the spinal tracts and tracing each neuron as they did in class to go over them at home, repeating this to explain to friends until they could do it perfectly. Despite lower grades in the spinal tracts section compared to other content questions, six of the fifteen survey respondents specifically mentioned using the spinal tracts diagram to trace and study at home when asked about most helpful

study methods. Seven respondents specifically mentioned practicing the cranial nerves representational gestures at home. Five students mentioned that the gestures were helpful for students to learn the functions of the cranial nerves.

In the interviews, more students mentioned practicing the gestures using the video to help them remember the anatomy and physiology of cranial nerves. All three interviewees said that the gestures helped them remember the order and number of the cranial nerves and their respective functions. In particular, the interviewees report rehearsing the gestures from class as part of their studying outside of class. All of them mentioned beginning with the spinal tracts picture and tracing the tracts with their finger as in class, and two mentioned rehearsing the gestures for the cranial nerves.

Clara (all names are pseudonyms) said "I did use your gestures video, I think that really helped because it helped like differentiate." She embellished her copy of the spinal tracts drawing with sticky notes added to the different neurons to help remember the function. She said, "I put the arrows then I chased it with my finger and it also helped me to have like the written explanation next to it." Grace reported that she used repetition with a friend to verbally drill the material. She said some gestures were helpful but "I also felt like oh gosh I forget the hand movement." She mentioned that using pointing gestures with the spinal tracts "definitely helps me to... go through it myself like with the hand gestures" because there was an image to use and trace, unlike the cranial nerves. Similarly, Sarah said "it helps me a lot to like imagine, like the picture of it, so I really just like traced my finger like we did in class up and down the tracts." Sarah also used repetition but split her time between repeating the gestures for the cranial nerves and spinal tracts and creating tables and drawings to accentuate her learning. She reported using the gestures of the cranial nerves during the exam to help remember the functions of those nerves; "On the test, I was thinking about, especially with like the abducens and the oculomotor [nerves] ... it really helped me to be able to like remember where my hands were whenever I would look at them to remember, which nerve moved in which way."

DISCUSSION AND IMPLICATIONS

This study was an investigation of the role of pointing and representational gestures in teaching and learning anatomy and physiology. Every effort was made to reduce variation between class sections, such as spending the same amount of time on content, providing the same assessments, and keeping the same class expectations for students with the exception of gesturing for section A only. Grounded in embodied cognition, we examined the effect of gestures to enhance sense-making and increase learning and retention of content.

Scores on spinal tracts questions did not improve as a result of the pointing gestures used in class. Historically,

students do not perform as well on spinal tracts questions compared to other content on this exam. The teacher used pointing gestures in both sections, so perhaps observing the teacher's use of gestures was sufficient for this content. Observing gestures benefits listeners' comprehension and improves memory encoding of the information (Church et al., 2017). In directing student attention to the specific neurons in the pathway, the students may have had adequate learning from that alone. The survey and interview responses indicate that tracing the spinal tracts was frequently practiced outside of class. However, one interviewee (Clara) indicated that while she traced the spinal nerves as we did in class, she also embellished her image with sticky notes of the specific functions of the neurons. In rehearsing the order of the pathway along with the function of the neurons, she may have created a more comprehensive study tool that furthered her understanding. This was reflected in her grade as Clara earned a 94% on this exam, placing her performance in the top 11% of all students in both sections. Future studies may explore other content areas to see if pointing gestures by students, especially in combination of rehearsal with other relevant information, helps students to understand and remember content better. If the teacher introduces gestures in a lesson, it may also be helpful to encourage students to take ownership of the gestures and use them in any way that supports their understanding. Perhaps having students create their own gestures to help learn and apply information would increase use and exam performance.

Scores on cranial nerves questions were significantly different between section A, who used gestures, compared to section B, who did not use gestures. Section A scored on average 4% better on cranial nerve questions compared to other content questions, while scores were nearly 7% worse for section B. This indicates that representational gestures may be more helpful than pointing gestures in helping students learn science content. As many variables as possible were kept the same between the two sections, the only major difference was the addition of gestures to section A. Students reported in the survey and interview watching the gestures video provided by the teacher, rehearsing the cranial nerve gestures on their own, and using gestures during the exam to help them remember the function of cranial nerves.

Moving forward, additional questions need to be addressed such as whether it is more helpful for students to create their own representational gestures or if it is sufficient to copy someone else's gestures to learn material. If the students create the gestures themselves, the students may take more ownership of them, use them in ways that benefit that individual's learning style, and may be more likely to use them. Other studies (Lam & Chan, 2020; Macken & Ginns, 2014; Novack & Goldin-Meadow, 2015; Roth, 2001) found an increase in learning when pointing gestures were used, and perhaps those gesture types can still be helpful in other content areas. If there are certain types of science content, such as factual knowledge, processes, or visual information like anatomy best

accompanied by gestures when teaching and learning, that needs to be elucidated. The results of this study encourages instructors to use gestures when explaining content, and in the future, we plan to be more specific in investigating the different kinds of gestures with different content.

Author contributions: **SW:** conceptualization, data curation, formal analysis, investigation, writing – original draft. **HH:** supervision; **SW** and **HH:** project administration, funding acquisition, methodology, and review and editing of the writing. Both authors approved the final version of the article.

Funding: The authors received no financial support for the research and/or authorship of this article.

Acknowledgments: The authors would like to thank the students who participated in this study.

Ethics declaration: This study was approved by the Institutional Review Board at Texas Christian University on 19 October 2021 with approval number 2021-176.

AI statement: No AI tools were used in writing this paper.

Declaration of interest: The authors declare no competing interests.

Data availability: Data generated or analyzed during this study are available from the authors on request.

REFERENCES

- Alibali, M. W., & Nathan, M. J. (2012). Embodiment in mathematics teaching and learning: Evidence from learners' and teachers' gestures. *The Journal of the Learning Sciences*, 21(2), 247-286. <https://doi.org/10.1080/10508406.2011.611446>
- Atit, K., Gagnier, K., & Shipley, T. F. (2015). Student gestures aid penetrative thinking. *Journal of Geoscience Education*, 63(1), 66-72. <https://doi.org/10.5408/14-008.1>
- Augustine, J. R. (2017). *Human neuroanatomy*. Wiley Blackwell.
- Barsalou, L. W. (2008). Grounded cognition. *Annual Review of Psychology*, 59(1), 617-645. <https://doi.org/10.1146/annurev.psych.59.103006.093639>
- Church, R. B., Alibali, M. W., & Kelly, S. D. (2017). *Why gesture?: How the hands function in speaking, thinking and communicating*. John Benjamins Publishing Company. <https://doi.org/10.1075/gs.7>
- Cook, S. W., & Goldin-Meadow, S. (2006). The role of gesture in learning: Do children use their hands to change their minds? *Journal of Cognition & Development*, 7(2), 211-232. https://doi.org/10.1207/s15327647jcd0702_4
- Crowder, E. M. (1996). Gestures at work in sense-making science talk. *The Journal of the Learning Sciences*, 5(3), 173-208. https://doi.org/10.1207/s15327809jls0503_2
- Galati, A., & Brennan, S. E. (2014). Speakers adapt gestures to addressees' knowledge: Implications for models of co-speech gesture. *Language, Cognition and Neuroscience*, 29(4), 435-451. <https://doi.org/10.1080/01690965.2013.796397>
- Goldin-Meadow, S. (2011). Learning through gesture. *Wiley Interdisciplinary Reviews: Cognitive Science*, 2(6), 595-607. <https://doi.org/10.1002/wcs.132>
- Goldin-Meadow, S., & Alibali, M. W. (2013). Gesture's role in speaking, learning, and creating language. *Annual Review of Psychology*, 64(1), 257-283. <https://doi.org/10.1146/annurev-psych-113011-143802>
- Hostetter, A. B., & Alibali, M. W. (2008). Visible embodiment: Gestures as simulated action. *Psychonomic Bulletin & Review*, 15(3), 495-514. <https://doi.org/10.3758/pbr.15.3.495>
- Kersting, M., Amin, T. G., Euler, E., Gregorcic, B., Haglund, J., Hardahl, L. K., & Steier, R. (2023). What is the role of the body in science education? A conversation between traditions. *Science & Education*, 33, 1171-1210. <https://doi.org/10.1007/s11191-023-00434-7>
- Lakoff, G., & Johnson, M. (1999). *Philosophy in the flesh: The embodied mind and its challenge to Western thought*. Basic Books.
- Lam, D. S. H., & Chan, K. K. H. (2020). Characterising pre-service secondary science teachers' noticing of different forms of evidence of student thinking. *International Journal of Science Education*, 42(4), 576-597. <https://doi.org/10.1080/09500693.2020.1717672>
- Lim, V. F. (2019). Analysing the teachers' use of gestures in the classroom: A systemic functional multimodal discourse analysis approach. *Social Semiotics*, 29(1), 83-111. <https://doi.org/10.1080/10350330.2017.1412168>
- Lunsford, E., & Diviney, M. (2020). Changing perspectives on anatomy & physiology: From killer class to gateway course. *Bioscene: Journal of College Biology Teaching*, 46(1), 3-9.
- Macken, L., & Ginns, P. (2014). Pointing and tracing gestures may enhance anatomy and physiology learning. *Medical Teacher*, 36(7), 596-601. <https://doi.org/10.3109/0142159X.2014.899684>
- Martínez-Marcos, A., & Sañudo, J. R. (2019). Cranial nerves: Morphology and clinical relevance. *Anatomical Record*, 302(4), 555-557. <https://doi.org/10.1002/ar.24106>
- Marwaha, A., Zakeri, M., Sangsiry, S. S., & Salim, S. (2021). Combined effect of different teaching strategies on student performance in a large-enrollment undergraduate health sciences course. *Advances in Physiology Education*, 45(3), 454-460. <https://doi.org/10.1152/advan.00030.2021>
- Mathayas, N., Brown, D. E., Wallon, R. C., & Lindgren, R. (2019). Representational gesturing as an epistemic tool for the development of mechanistic explanatory models. *Science Education*, 103(4), 1047-1079. <https://doi.org/10.1002/sce.21516>
- McNeill, D. (1992). *Hand and mind: What gestures reveal about thought*. University of Chicago Press.

- Novack, M., & Goldin-Meadow, S. (2015). Learning from gesture: How our hands change our minds. *Educational Psychology Review*, 27(3), 405-412. <https://doi.org/10.1007/s10648-015-9325-3>
- Padalkar, S., & Ramadas, J. (2011). Designed and spontaneous gestures in elementary astronomy education. *International Journal of Science Education*, 33(12), 1703-1739. <https://doi.org/10.1080/09500693.2010.520348>
- Pulvermuller, F. (2005). Brain mechanisms linking language and action. *Nature reviews. Neuroscience*, 6(7), 576-582. <https://doi.org/10.1038/nrn1706>
- Roth, W.-M. (2001). Gestures: Their role in teaching and learning. *Review of Educational Research*, 71(3), 365-392. <https://doi.org/10.3102/00346543071003365>
- Roth, W.-M., & Welzel, M. (2001). From activity to gestures and scientific language. *Journal of Research in Science Teaching*, 38(1), 103-136. [https://doi.org/10.1002/1098-2736\(200101\)38:1<103::AID-TEA6>3.0.CO;2-G](https://doi.org/10.1002/1098-2736(200101)38:1<103::AID-TEA6>3.0.CO;2-G)
- Shapiro, L., & Stolz, S. A. (2019). Embodied cognition and its significance for education. *Theory and Research in Education*, 17(1), 19-39. <https://doi.org/10.1177/1477878518822149>
- Ünsal, Z., Jakobson, B., Wickman, P.-O., & Molander, B.-O. (2018). Gesticulating science: Emergent bilingual students' use of gestures. *Journal of Research in Science Teaching*, 55(1), 121-144. <https://doi.org/10.1002/tea.21415>

