CITATION: Tang, K.S., Jeppsson, F., Danielsson, K., & Nestlog, E. B. (2022). Affordances of Physical Objects as a Material Mode of Representation: A Social Semiotics Perspective of Hands-on Meaning-making. *International Journal of Science Education*. https://doi.org/10.1080/09500693.2021.2021313

Affordances of Physical Objects as a Material Mode of Representation: A Social Semiotics Perspective of Hands-on Meaning-making

Kok-Sing Tang[1], Fredrik Jeppsson[2], Kristina Danielsson[3, 4], Ewa Bergh Nestlog[3]

[1]Curtin University, [2]Linköping University, [3]Linnaeus University, [4] Stockholm University

Abstract

This paper examines the affordances of physical objects (e.g., apparatus, models, manipulatives) as they were used by teachers and students to make meaning in coordination with their speech and gestures. Despite the pervasive use of physical objects as material and tactile resources in hands-on investigations or demonstrations, there have been few attempts to analyze their role and function in meaning-making, in the same way that researchers have previously done for other modes of representation such as speech, written text, diagram, and gesture. Using social semiotics as a theoretical framework, we conceptualize physical objects as a semiotic mode with a particular affordance for making meaning that involves embodied actions and manipulation of tools. Based on a multimodal discourse analysis of numerous classroom situations, we illustrate how physical objects as a mode have four unique affordances for meaning-making in science classrooms. These affordances are: (a) enacting material interaction, (b) providing evidential meaning, (c) orientating three-dimensional spatial meaning, and (d) sensitizing experiential meaning. The implication of why we should use physical objects to support or value-add science meaning-making is then discussed.

Keywords: classroom discourse, multimodality, new materialism, representation, semiotics, tactile manipulation

Introduction

The use and manipulation of physical objects in a demonstration or investigation of natural phenomena is a common practice in science education. The usefulness of these objects (e.g., physical models, scientific apparatus, everyday items) is often conceived in a number of ways. First, physical objects are often used in hands-on activities to generate interest and support learner engagement, particularly as an alternative to the dominance of teacher talk in a typical lesson (Buxton & Lee, 2014; Holstermann et al., 2010). Second, the use of physical objects provides a practical work experience that is more aligned with the inquiry nature of science (Chen et al., 2014; Perin et al., 2019). Such perceived advantages of using physical objects are typically reported by teachers and students through surveys and interviews (e.g., Abrahams & Saglam, 2010; Martin et al., 2014).

Despite the importance of physical objects, few studies seek to understand their usefulness by examining how teachers and students actually use them to make meanings in various classroom interactions. The focus on *meaning-making* (semiosis) pays attention to how people interact with physical objects in situ (e.g., learning or teaching science), instead of retrospectively asking for their views and perceptions. Specifically, few researchers have empirically investigated the relative *affordance* of physical objects in meaning-making in relation to other multimodal resources like verbal language, diagram, or gesture. For instance, few have asked the question of how does a physical object afford a user to make certain meanings in a situational interaction that would not be possible with other multimodal resources?

The study of multimodality (multiple modes of representation) and materiality (physical properties of a cultural artifact) are currently two areas of interest in science education (Hand et al., 2016; Hetherington et al., 2018). From the perspective of social semiotics, the use of physical objects is considered one of several semiotic modes that people use to make meanings (Van Rooy & Chan, 2017). Researchers in science education have over the years investigated the affordance of the following modes as a meaning-making resource used in science classrooms: verbal language (e.g., Halliday & Martin, 1993; Lemke, 1990), visual representations (e.g.,Kress & van Leeuwen, 2006; Tang et al., 2019), mathematical symbolism (e.g., Lemke, 2003; O'Halloran, 2000), and gestures (e.g., Givry & Roth, 2006). However, the affordance of physical objects as a semiotic mode has not been sufficiently theorized and investigated empirically. At the same time, researchers in science education have often neglected the role of physical objects in human interactions (Hetherington et al., 2018).

The purpose of this study is to investigate, both theoretically and empirically, the affordance of physical objects as they are used by teachers and students in classroom interaction to make science meanings. The study aims to inform our understanding of why we should use physical objects to support science learning activities, not based on our perceived notion of their intrinsic material property and potential, but based on an empirical investigation of what people actually do with physical objects in various meaning-making interactions. Toward this end, this study first theorizes physical objects as a semiotic mode based on a social semiotic framework. It then applies a multimodal discourse analysis to numerous classroom videos from a range of situations in order to examine the affordance of physical objects and its contribution to science meaning-making.

Research on Physical Objects in Science Education

There have been multiple terms used to describe the instructional resources that involve the use of physical *things* in the classroom (e.g., object, manipulative, apparatus, sample, realia, tactile representation) as well as their associated *activities* (e.g., hands-on, demonstration, investigation, experiment, manual-technical operation). In this paper, we use the term "physical object" to encompass these various usages, so long as the following criteria are met: all physical objects must be real and tangible, they must obey the laws of nature, and they can be physically manipulated. Physical objects can include: (a) scientific apparatus and samples such as beaker, microscope and chemicals; (b) educational models and demonstration kits such as a ripple tank, ball-and-stick model, anatomical model; and (c) everyday items deliberately or spontaneously used by teachers or students, including flashlight, paper, cardboard, water bottle, and slinky coil.

More than 20 years ago, Roth (1999) stated that there was virtually no research that show how meaning arises from hands-on activities with physical objects despite their prevalence in school science. In an analysis of many classroom conversations, Roth showed that speech alone is insufficient to understand what was said and learned during those conversations. Instead, discourse is always grounded in our physical interaction with the material world. It is thus crucial to understand how the manipulation of materials and tools allow students to make meanings in science. Since then, there has been some research over the last two decades focusing on: (a) the role of multimodality in social semiotics and (b) the role of materiality in new materialism.

Social semiotics

Research from social semiotics has examined various semiotic modes (e.g., verbal language, image, gesture) that mediate learning and treated physical objects as one of multiple modes used in the classroom. In a seminal study, Kress et al. (2001) highlighted the complex ways that science teachers orchestrate a range of semiotic modes to support their teaching as well as how the process of student learning develops as a “dynamic process of sign-making” (p.27). Not only did Kress et al.’s (2001) study highlights the multimodal nature of science classroom communication, it also illustrates that every mode has a unique “functional specialization” (i.e. affordance) to achieve some meanings for the learner. They went on to expand on the affordances of the visual and gestural modes, but not comprehensively on the material mode. In one of their examples on blood circulation, they briefly mentioned the use of a human body model as a focal object to mediate the teacher's speech and actions. We argue that there are more affordances in using the material mode, which will require a more systematic investigation in this paper.

Other studies informed by social semiotics have examined how teachers and students coordinate and integrate a range of multimodal representations in their interactions. These studies were informed by Lemke's (1998) postulate that the integration of multiple modes increases or "multiplies" the potential for constructing knowledge in science and science teaching. Accordingly, scientific knowledge or concepts are not communicated through a verbal mode alone, but are actively constructed as "semiotic hybrids, simultaneously and essentially verbal, mathematical, visual-graphical, and actional-operational" (Lemke, 1998, p.87). By far, the most common multimodal integration that have been examined are a combination of verbal, visual, and gestural modes (e.g., Danielsson, 2016; Ge et al., 2017; He & Forey, 2018; Moro et al., 2020; Tang, 2020; Tang et al., 2014). By comparison, studies that examined the integration of meaning involving physical objects are much fewer. For instance, Moro et al. (2020) focused their multimodal analysis only on diagrams and gestures even though the activity involved the use of a spectroscope in a laboratory session to demonstrate the spectrum of light.

The pedagogical value of using physical objects in hands-on exploration is frequently emphasized by researchers working with language learners (e.g., Jakobson et al., 2018; Ünsal et al., 2019; Varelas et al., 2014; Wu et al., 2019). Buxton and Lee (2014) argue that because physical manipulatives are less demanding on language proficiency, they provide a level of access to language learners who are learning science and the language of instruction at the same time. In a systematic review of the literature from 1995 to 2019, Williams and Tang (2020) found 30 studies that indicated the use of tactile representations to support language learners in science. The review suggests a growing recognition of using a material mode to provide equal opportunities for all science students regardless of their linguistic background. However, most of these studies only mentioned the pedagogical importance of tactile representations instead of empirically investigating how they were actually used by teachers and students during classroom discourse.

New Materialism

Another emerging perspective on physical objects comes from a socio-materialist view now generally known as new materialism (Barad, 2007), which is currently gaining traction in science education (Milne & Scantlebury, 2019). According to Weinstein (2010), this materialist perspective originated from pioneering work in the sociology of science (e.g., Latour, 1987; Pickering, 1995) and seeks to understand how human knowledge and practice are embedded in a material environment (Sørensen, 2009). By examining how humans and non-humans are intertwined within a "technoscience" network, Latour (1987) argued that materials have shared agency in making things happen. Pickering (1995) further built on this idea by ascribing intentionality to human agents while introducing the notion of *performativity* to denote our dependency on materials in our actions. Thus, science is a performance that is temporally emergent in practice based on a cooperative interplay between humans and materials. Pickering (1995) calls this interplay the "mangle of practice" where humans and materials are engaged in a dance of resistance and accommodation. For instance, physical objects often offer resistance to the running of an experiment which would necessitate a corresponding accommodation in practice from the scientists.

The ideas of material agency and performativity imply a different view of science away from a representational idiom to a performative one (Olohan, 2016). Thus, science is just not a body of static representations created by humans but science should be seen as a performative engagement of human and material agency in the world. In the same way, in our theorization and treatment of physical objects in science learning, we must bear in mind that the material-operational mode is not an independent and ready-made resource that is readily available for use as a set of representations. Instead, we must consider it as a performative and contingent practice that is always dependent on a nexus of human and non-human interactions.

Theoretical Framework: Mode, Materiality & Affordance

This study is informed by social semiotics – a theory developed to understand how people use various semiotic modes to make meanings in a community (Kress, 2010). According to Halliday (1978), language is a *semiotic mode* that comprises a system of culturally shaped signs (e.g., sounds, alphabets, logograms) that are used and moulded over time by a particular community into a meaning-making tool. This key tenet is not only limited to verbal language, but it also applies to non-verbal modes that have been developed in multiple communities throughout history (e.g. image, hand signal, musical notation). All these semiotic modes function as a meaning-making tool to serve three general types of meaning-making functions (Halliday, 1978). These three functions are: (a) ideational – to construct and represent our ideas and experiences of the world, (b) interpersonal – to enact our interaction, relationship, and stance with others and our experiences, and (c) textual – to organize text or artifact by connecting its disparate parts into a coherent whole.

Every sign requires a material substance for the sign to be made and further developed into a semiotic mode. This concept of materiality is consistent with Peirce's (1986) semiotics which posits that meaning is linked to a material sign through the process of signification. Thus, every meaning-making sign has a material as well as a semiotic dimension (Lemke, 1998). In terms of the material dimension, the intrinsic characteristic of a material shapes the making-making affordance of a mode (e.g., possibilities, constraints). For example, the affordance of speech as a mode is based on the materiality of discrete sound, which gives rise to a temporal and transient characteristic in speech. As for the semiotic dimension, through the repeated use of a sign (e.g., sound, word, symbol) by a community of people, the sign becomes associated to a particular meaning and eventually a system of signs emerged to be used as a meaning-making resource. In other words, the material dimension of a sign depends on its intrinsic characteristic (or materiality) while the semiotic dimension depends on how people use the sign in situ to make meanings.

In science education, Van Rooy and Chan (2017) classify five major modes commonly used in the classroom based on their different affordances. These modes are:

1. *Verbal-linguistic* – the use of spoken and written language in various cultures (e.g., English, Swedish).
2. *Visual-graphical* – the use of image systems such as schematic diagrams, drawings, photographs, and graphs.
3. *Mathematical-symbolic* – the use of scientific-mathematical notations including algebraic symbols, number systems, equations, and formulae.
4. *Gestural- kinesthetic* – the use of hand and body movements, including various hand gestures, gaze, and position of bodies.
5. *Material-operational* – the configuration of physical objects and their usage to support the activity of science teaching and learning.

The unique affordances of verbal-linguistic, visual-graphical, mathematical-symbolic, and gestural-kinesthetic have previously been investigated in social semiotics (e.g., Kress & van Leeuwen, 2006; Lemke, 2003; Martinec, 2000; O'Halloran, 2000). For instance, the affordance of verbal-linguistic mode largely relies on a categorical system of words to make typological meaning or "meaning-by-kind" that is suitable for specifying paradigmatic (mutually exclusive) distinctions, such as yes/no, cat/dog, before/after, arm/leg, and anode/cathode. By contrast, the visual-graphical mode is more suitable for making topological meaning or "meaning-by-degree" (e.g., by how much), due to its spatial and quantitative affordance (Lemke, 2003). For the material-operational mode however, not much is currently known about its semiotic affordance.

Therefore, the investigation of physical objects as a form of semiotic resource for science meaning-making is one of the "last frontiers" to be explored and investigated in multimodality (after verbal, visual and gestural modes). This research gap informs the purpose of this study and the following research question, which is: What are the unique semiotic affordances of physical objects as a material-operational mode?

Methodology

Research Design, Data & Participants

This study utilized a collective case study (Stake, 2000) to analyze data from three research projects. These research projects involved teachers and students from a range of science subjects and levels, including primary school science, secondary school physics and chemistry, and first year undergraduate chemistry. Despite various classroom environments, the projects all shared two things in common. First, the research focus centered on the use of representations. Second, the primary data source was classroom videos that captured the rich interactions among the teachers and students as they used multiple representations in situ to make meanings. These videos were mostly recorded by several researchers using high definition video cameras mounted on tripods, with one camera capturing the whole class while another camera focused on one student group or other interesting interactions. Students' artifacts and interviews were also collected as secondary data source.

The rationale of using a collective case study is informed by its usefulness to provide a detailed and holistic understanding of human interactions within a bounded system (i.e. case). For this study, a case is defined as a contextual and time-bounded event that dynamically influences how people make meanings. The event typically comprised a collective activity involving a number of participants, their surrounding environment, as well as the moment-by-moment coordination of all relevant meaning-making signs during the event. Multiple cases were analyzed and described to provide insight to the issue in question – the use of physical objects in situational contexts.

The multiple cases in this study involved the following participants from the authors' research projects in Sweden, Singapore and Australia. The Swedish project was carried out in one public school in a small town. The teachers were recruited for the project based on recommendation from science educators at the nearby university. The data used for this study involved 25 students from one mixed gender fifth grade class. All the authors were involved in the project. To facilitate the collaboration among the authors as well as the illustration in this paper, the transcripts from the Swedish classrooms were translated into English. The transcription was carried out with the aim to preserve the structure of the original linguistic choices, at times resulting in unidiomatic expressions in English. The ethical considerations for the project were approved by the Swedish Ethical Review Authority (registration number 2019-02715).

The Singaporean project involved four teachers in two public schools. One physics and one chemistry teacher from each school were recruited based on their school leaders' recommendation. Subsequently, one class from each teacher was selected for classroom observations. A total of 107 students from ninth to tenth grade took part in the research. Lastly, the participants in the Australian project were recruited from first-year chemistry undergraduates at a large public research university in a capital city. Twenty-two volunteers, with varying degrees of background knowledge in chemistry, took part in a project focusing on chemistry representations. Only the first author was involved in the Singaporean and Australian project, and English was the only language used in these projects. The ethical considerations for these projects were approved by the Institutional Review Board of (IRB-2013-04-012) and the Human Research Ethics Committee of (HRE2018-0040) respectively.

As this study drew on multiple cases across countries and cultures, the purpose of our analysis is not to make universal claims or examine typicality in the use of physical objects, but rather to present "telling cases" (Mitchell, 1983) that reveal insights into the semiotic role of physical objects in a variety of diverse situations important to science education. The use of multiple data sources across countries was therefore carried out with the rationale to increase the richness of data and broaden the scope of analysis to various topics and grade levels in science education. This purpose aligns with the methodological choice of using a collective case study design to generate insights that can enable researchers to establish theoretical connections between classroom events and the use of physical objects (Stake, 2000).

Analytical Procedures & Methods

The video data were processed as part of the larger projects to identify episodes within the chronological flow of events in the observed lessons. An episode is segmented according to the participants' interaction pattern. Following the analytical steps in interactional ethnography (Erickson, 1992), the boundaries of an episode is marked by the shifts in the participation structure. For example, a teacher coming to join a group discussion often marks a shift in the interaction in terms of the speech pattern, gaze direction, and bodily orientation. A content listing (Jordan & Henderson, 1995) indexing the activity type, description, and dominant representations for each episode had also been carried out. For this study, episodes that had been tagged with keywords like *demonstration*, *experiment*, *hands-on*, *material*, and *model* were selected for viewing with the research question in mind.

With our theoretical framework as an interpretive lens, we paid attention to not only the participants' use of physical objects, but also their accompanying spoken utterances and gestures in the video. Preliminary assertions were inductively generated and discussed among the authors in meetings and through email communications. In addition, episodes that illustrate our preliminary assertions were selected for a more detailed micro-analysis.

The micro-analysis was conducted mainly by the first author with assistances from the other authors. The episodes were transcribed with the purpose of facilitating a multimodal discourse analysis (Baldry & Thibault, 2006). First, Halliday's (1985) transitivity system was used to analyze verbal language in terms of the semantic processes that connect to our ideas and experiences. In verbal language, every clause realizes one of six types of processes through the main verb in that clause. These processes are material (e.g., move), existential (e.g, is), relational (e.g., is, has), verbal (e.g., speak), behavioral (e.g., cry), and mental (e.g., think). This transitivity analysis was also generalized and applied to the analysis of gestural-kinesthetic and material-operational modes.

In a gestural mode, the actions of our hand play a similar role to the transitivity processes in verbal language, but now it is the hand gestures rather than words that realize the process (Martinec, 2000). Gestural actions can be classified into material, behavioral, verbal, mental, and relational processes as well. Material process is an action directed at others or physical objects (e.g., pushing a table, scraping a surface), while behavioral, verbal, and mental processes are directed to oneself (see Lim, 2019). Transitivity is often made with iconic gestures, which are gestures that resemble or share certain features with an object or action being represented. Besides iconic gesture, there are also performative and deictic gestures. Performative gesture is a kind of non-communicative gesture whose main function is to execute a task, such as handing out worksheets or setting up an apparatus (Lim, 2019). Deictic gesture is a pointing gesture used to direct attention toward a person, object, or screen. It often co-occurs with speech and it provides a relational (indexical) action to link an utterance to something in the environment.

In a material-operational mode, it is possible to have material, relational, and existential processes. Material process arises when we observe that something is happening to an object (e.g., moving, getting darker) in the physical world. Relational process occurs when we relate an attribute to an object or an object to another object. For example, in a red ball, the attribute of redness (which has a material basis in dye) is connected to a physical ball. Existential process occurs when we can see or touch a real object, thus justifying its existence in the physical world. Table 1 shows an example of the material, relational, and existential processes in a verbal, gestural, and material mode. We will also see some examples of how these processes shape meaning-making later.

[INSERT TABLE 1 AROUND HERE]

In sum, by breaking down and organizing the meaning-making actions involving speech, gesture, and manipulation of objects into individual transitivity process, what is useful in this approach is that we can identify and compare the processes from multiple semiotic modes occurring at the same time.

Finally, in an iterative process, this multimodal discourse analysis informed and refined our preliminary assertions, which then informed our selection for more episodes to be further analyzed, and so on until we arrived at a saturation where no further understanding and theory development can be derived from the data. Throughout this process, the authors checked on one another's interpretation in order to establish some common understanding and joint consensus. For instance, the micro-analysis conducted by the first author was frequently checked by the other authors. Any disagreement and ambiguity in the author's claim and interpretation were discussed collectively. The discussion subsequently led to further clarification in the interpretation or modification of the claim, until the disagreement was resolved.

The trustworthiness of the study was also strengthened through triangulation of multiple data sources with the video data, notably students' artifacts (e.g., worksheets) and interviews. When a video showed students recording their observations on paper through writing or drawing, we would check those artifacts to extend our interpretation. These data were used to support our search for confirming and disconfirming evidence during the analysis (Antin et al., 2015).

Findings

Based on the analysis of classroom video data, we found that physical objects as a material-operational mode have four major semiotic affordances for making meanings in science classrooms. These affordances are: (a) enacting material interaction, (b) providing evidential meaning, (c) orientating three-dimensional (3D) spatial meaning, and (d) sensitizing experiential meaning. In what follows, we elaborate and illustrate these affordances based on telling cases drawn from the analysis.

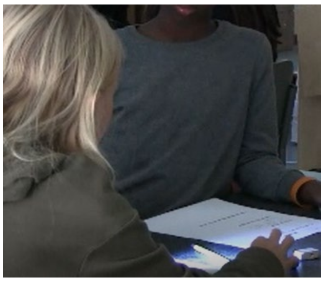
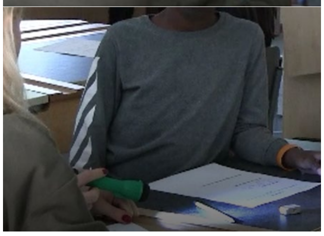
Enacting material interaction. The first semiotic affordance arises from the fact that physical objects in the world act and react according to the laws of nature; for example, light travels, ball drops, chemicals react, and cells divide. This affordance accounts for why many science educators frequently use physical objects to demonstrate a natural phenomenon for students to observe. However, the meaning-making role of such usage in coordination with speech and gestures has seldom been analyzed to understand how physical objects add value to the teaching and learning process.

As an illustration of this affordance, Excerpt 1 shows an interaction between a grade 5 student and a teacher in a small group discussion to explain how a shadow was formed. This excerpt was taken from the Swedish research project, but it is also a typical example that could be found in similar instances. As shown in the excerpt, the students asked the teacher to come to the group and one student, Alice, then read a question from a worksheet, "where does the shadow appear?" As a response to guide the students' focus, the teacher used a flashlight and pencil, which were material resources available in every group, and performed a spontaneous demonstration of shadow formation using those objects while the students watched (see figures in Excerpt 1).

To understand the semiotic dimension of the meaning-making, we need to analyze the co-occurring speech and gesture when the shadow was created. This requires a detailed analysis of the ideational meanings made by the verbal, gestural, and material modes through their transitivity processes as previously described. In all the transcripts that follow, every clause in the spoken utterance constitutes a line in the transcript. A dot "." indicates a brief pause, two dots ".." indicate a substantial pause (more than 2 seconds), and three dots " . . . " indicate the omission of utterance deemed irrelevant to the analysis.

Excerpt 1 (**bold** – material transitivity; <u>underline</u> – conjunction, *italics* – metadiscourse)

Line	Speaker	Spoken utterance	Gesture & Material Manipulation
1	Alice	Where does the shadow appear?	
2	Teacher	The shadow appears there, *can you see that*?	
3	Teacher	<u>Then</u> why does it become shadow there?	
4	Alice	The sun. or. <u>when</u> the **flashlight. it shines here**	

5	Alice	<u>And then</u> **it gets behind**	
6	Alice	<u>Because</u> the sun.. <u>because</u> **it can't.. uh, shine there**?	
7	Teacher	Exactly, exactly. <u>Because</u> .. **something covers**, right?	
8	Alice	Mm.	
9	Teacher	Yeah exactly	

In line 1 and 2, Alice's question and the teacher's reply consisted of existential processes (e.g., shadow appears) that described the observed phenomenon. These utterances coincided with the teacher's deictic gesture pointing at the shadow as well as her performative creation of the shadow phenomenon. This harmony of verbal-linguistic, gestural-kinesthetic, and material-operational modes produced an agreement among the teacher and students concerning the existence of the desired phenomenon (i.e., shadow), which subsequently allowed them to make further meaning of it.

With the existence of the shadow established, the teacher next asked for an explanation of the shadow phenomenon in line 3, which subsequently prompted a chain of material processes in Alice's utterances from line 4 to 7 (e.g., flashlight *shines,* something *covers*.) These material processes as verbalized from Alice's utterances mostly mirrored the real material interactions enacted by the physical objects. In particular, there were three crucial material interactions created in the demonstration: (a) light traveled from flashlight to pencil, (b) pencil blocked the light, and (c) light could not continue, thus causing shadow (an absence of light). However, when we examine closely Alice's explanation from line 4 to 6, she only articulated two of those material processes – flashlight "*shines* here/there" and shadow "*gets* behind." She omitted the part about the pencil blocking the light.

This particular case is telling because it highlights the entanglement between the material and semiotic dimensions of the observed phenomenon. When Alice said, "it shines here. And then it gets behind," she might have assumed the material interaction of pencil blocking the light was already obvious and thus omitted the role of opaque pencil. It is as though she thought the material interaction in this demonstration could "speak for itself." The teacher's followed-up in line 7 shows that she noticed the conceptual gap in Alice's reply and thus added "something covers" to supplement the missing material process. Therefore, although both Alice and the teacher performed and observed the same phenomenon with the physical objects, they emphasized slightly different meanings according to their perspectives. For Alice, she only focused on the light path while the teacher wanted to also emphasize the opacity of an object in creating shadow.

This case illustrates that physical objects provide the empirical basis for science meaning-making through this particular affordance of enacting material interaction. However, we must remember that meaning is not found in or enacted by material alone, but meaning must be constructed through a joint coordination of human actions (i.e., utterances, gestures) and physical objects. Furthermore, we need to consider the affordances of the verbal and gestural modes in the joint meaning-making process. For instance, the role of conjunctions (as *underlined* in Excerpt 1) and deictic gestures are crucial in constructing the explanation of how a shadow is formed. Another function of verbal language is the use of metadiscourse to signal the epistemological source of our knowledge or inference. This was seen in line 2 when the teacher said, "can you see that?" The function of a metadiscourse will be further elaborated next.

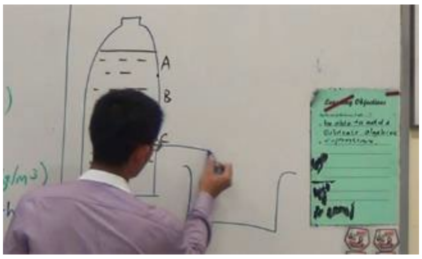
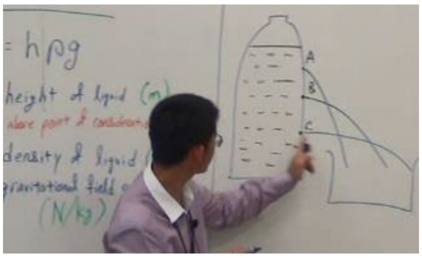
Providing evidential meaning. The second affordance of physical objects is the provision of empirical evidence for science meaning-making. This affordance is critically important because scientific knowledge is fundamentally built on an inquiry of and with the material world. Similar to the earlier discussion where physical objects do not intrinsically possess any meaning, physical objects also do not provide any evidence on their own. Instead, evidence must be actively constructed as a form of social practice by coordinating our semiotic actions with the use of physical objects (Latour & Woolgar, 1979) under a particular theoretical paradigm (Kuhn, 1962). In the case of the science classroom, an experiment alone does not provide any evidence, but it is through the guided actions of a teacher that "*some thing* [in the experiment] is turned into an epistemic object" (Roehl, 2012, p. 57).

In classroom discourse, teachers seldom openly communicate an epistemological commitment to empirical inquiry (Lundqvist et al., 2009), even when they actively use physical objects during demonstration and investigation. They do not directly talk about the source of knowledge as deriving from our sensory experience with objects in the world. However, through their metadiscourse (talk about talk), we can examine how teachers subtly imply the evidential source of scientific knowledge (Tang, 2017). One particular type of metadiscourse is called an "epistemology marker" (Vande Kopple, 2012), which signals a person's stance toward the evidential status of the propositional content. In excerpt 1, we saw an instance of epistemological markers when the teacher asked, "can you see that?" as she created a shadow using a flashlight and pencil. Such remarks do not merely direct our attention toward the demonstration, but they also convey the evidential basis of how we know the information that we communicated is true.

In the analysis, it was found that epistemological markers were often used with physical objects to establish the evidential basis of knowledge claims in the classrooms. This is best illustrated in the next example that involved a demonstration of water pressure. In this demonstration that occurred in the physics classroom in Singapore, a teacher poured water into a plastic bottle that had three holes made at different vertical positions. The ensuing phenomenon with three different water jets spurting out was used as an evidence for the variation of pressure with water depth:

Excerpt 2 (**bold** – material transitivity; <u>underline</u> – conjunction, *italics* – metadiscourse)

Line	Speaker	Spoken Utterance	Gesture & Material Manipulation
1	Teacher	<u>So</u>, *we're going to see* whether point A, point B or point C has the highest pressure	
2	Teacher	<u>And</u> *how do we see that*, right? Simply, it's by.. <u>because</u>.. (Handling the apparatus)	
3	Teacher	Okay. <u>So</u> *how do we judge that*? Simply, <u>if</u> it's from. <u>if</u> it can.. <u>if</u> it can **shoot the furthest**.	
4	Teacher	Okay, <u>then</u> it has the highest pressure...	
5	Teacher	(Pours water into the bottle followed by a discussion with the students)	
6	Teacher	Okay, <u>as</u> *we can see right, from the experiment*, roughly how does it look like, right? I'll draw it for you the. the spurting.	

7	Teacher	Okay, <u>so</u> this one will actually **spurt like this**... (Comments and draws the spurting for C, followed by B, and then A.)	
8	Teacher	Alright, <u>so</u> *we can see,* C actually has the highest pressure	

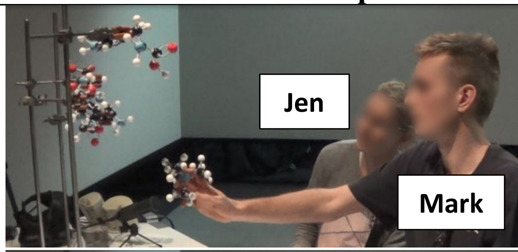
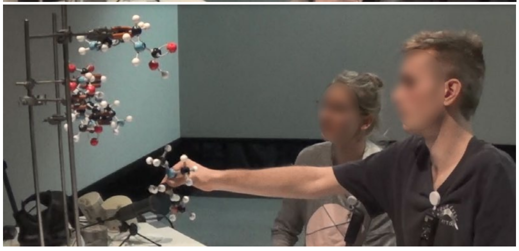
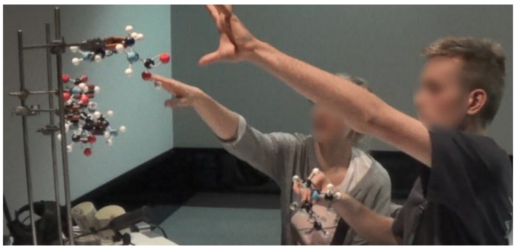
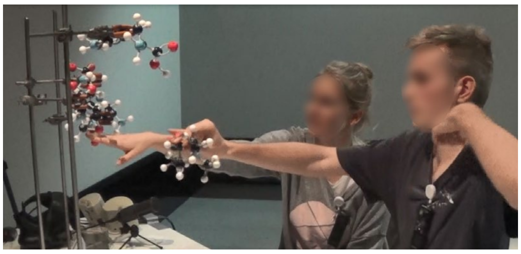
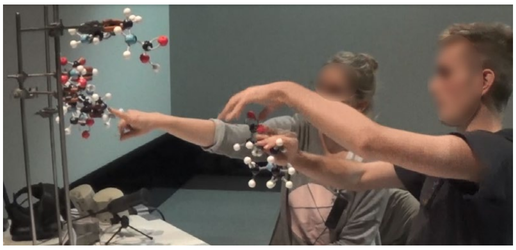
The purpose of this demonstration was to let the students “see” that point C (lowest hole in the bottle) would have the highest pressure “if it can shoot the furthest” (line 3). In other words, the demonstration was to establish a casual claim that “pressure changes with depth” based on the evidence of three varying length of water jets. The teacher used epistemological markers five times in lines 1, 2, 3, 6, and 8 (as *italicized*) to establish the evidential basis of determining which point had the highest pressure. The phrase “so how do we *judge* that?” in line 3 is particularly telling as it signaled the empirical basis of determining “the highest pressure” based on whichever “can shoot the furthest.” These commentaries to the source of evidence effectively revealed the teacher’s epistemological stance based on sensory experience as well as his view concerning the role of physical objects to support this belief. Moreover, these epistemological markers also served as the semiotic actions that made salient certain material features in the demonstration and subsequently rendered them into an “epistemic object” for the evidence (Roehl, 2012).

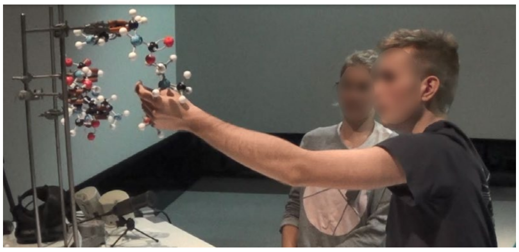
Orientating 3D spatial meaning. The third affordance arises from the three-dimensionality of physical objects. This affordance is often discussed in education research in terms of using 3D models to facilitate visualization of complex spatial arrangements (e.g., Kress et al., 2001). 3D models help students orientate themselves to the spatial aspects of an object in a three-dimensional space. This is something that cannot be achieved with a visual-graphical mode that is restricted to two dimensions.

Similar to the previous examples, we need to differentiate between the intrinsic materiality of a 3D object and the semiotic actions that people take to interact with the object in a 3D space. An important idea to consider here is the perspectival viewing between a viewer and object. When a 3D image is drawn on paper or rendered on a flat screen, the orientation of this image remains fixed regardless of the viewing direction. However, this is not the case for a real physical object. The orientation of this object changes depending on where a viewer is looking from in relation to it. Therefore, the affordance of 3D spatial meaning must thus be examined from the perspective of the viewer in relation to the object (semiotic dimension), and not just the intrinsic three-dimensionality of the object alone (material dimension). In addition, the affordance of 3D spatial meaning is both an ideational and interpersonal meaning. The ideational meaning afforded by a 3D object arises from the spatial information about the object while the interpersonal meaning arises from the interaction between the viewer and object.

We use Excerpt 3 to show how the 3D affordance of physical objects shape students' interaction and meaning-making in terms of perspectival viewing. Two chemistry undergraduates from the Australian project were asked to explain how an acetylcholine molecule reacts with the catalytic triad inside an acetylcholinesterase enzyme. Using a ball-and-stick model, four molecular structures were constructed to represent acetylcholine and the three amino acids of the catalytic triad – glutamate, histidine, and serine. The students were asked to use the acetylcholine molecule and demonstrate how it reacts with the three amino acids, which were fixed on retort stands (see video snapshots in excerpt 3):

Excerpt 3 (**bold** – material transitivity; <u>underline</u> – conjunction, *italics* – metadiscourse)

Line	Speaker	Spoken utterance	Gesture & Material Manipulation
1	Mark	<u>So</u> it's like. *I'm trying to visualize* like.. (inaudible) that would be. would be like..	
2	Mark	It's like that, isn't it..	
3	Teacher	Where is the electron rich area in the gorge?	
4	Mark	The rich. It was up here.	
5	Jen	Up here.	
6	Jen	<u>And then</u> down.	
7	Mark	Down here	
8	Jen	Wasn't it?	
9	Mark	That's the electron. poor?	
10	Jen	Yeah	
11	Mark	<u>And</u> this is electron rich..	

12	Mark	So it'll be like.. that	
13	Mark	So when **it reacts**.	
14	Mark	Then it will probably **react** with this one.	

For the analysis of interpersonal meaning, we focus on the students' bodily orientation with respect to the physical object. In the beginning of excerpt 3, Mark and Jen were figuring how to orientate the acetylcholine molecule such that it could connect to the three amino acids. Grabbing the ball-and-stick model of acetylcholine, Mark rotated the model freely in a 3D space for several seconds as he tried to "visualize" its orientation in relation to the amino acids (lines 1-2). The relative perspectives from where the students were looking at the model were important in shaping their visualization and interpretation. This could be seen from the shifts in their heads and bodies as they orientated themselves to match the orientation of the 3D models, most prominently by Jen from line 1 to 2.

For the analysis of ideational meaning, we pay attention to the chemistry content that was represented through the manipulation of the ball-and-stick model. In line 3, the students were prompted to consider the electron density of the molecules as they orientated the acetylcholine molecule. This led them to identify the electron rich area (lines 4-5) and electron poor area (lines 6-10) within the catalytic triad (which is inside the "gorge" of acetylcholinesterase enzyme.) Subsequently, Mark identified the electron rich area in the acetylcholine molecule in line 11 by pointing at the red-colored balls, which represent the oxygen atoms in the molecule. (Oxygen ions tend to have higher electron density in molecular bonding.) This information subsequently helped Mark to re-orientate the acetylcholine molecule such that its electron-rich region was attracted to the electron-poor region of the catalytic triad, as seen in line 12. In this interaction, the relational processes represented by the different colors in the ball-and-stick model (e.g., red ball representing oxygen) play an important role in the ideational meaning-making.

Sensitizing experiential meaning. Lastly, physical objects not only facilitate perspectival viewing in a 3D space, but they can also be touched and physically manipulated. The tactile sensation and haptic feedback mediate both ideational and interpersonal meanings. Ideationally, touch allows us to construct our experiences with natural objects and phenomena, for example in terms of hot/cold, hard/soft, push/pull, heavy/light, dry/wet, and watery/slimy/sticky. These experiential distinctions are essential for making meanings of science content in many topics.

Interpersonally, the sense of touch is always personal as it involves some kind of sensation and "feeling" from an individual. Cranny-Francis (2011) argues that touch creates an affective connection between an individual and an object in most cultures. It is a key factor that generates engagement between the person and the object, particularly in museums that allow a fully embodied experience (Candlin, 2010). In a study of student learning using a remote microscopy, Jones et al. (2004) found that students who received haptic (tactile and kinesthetic) feedback with the tool had significantly better attitudes toward the learning experience as well as developed better conceptual models of virus morphology, compared to those who did not receive haptic feedback.

The embodied sensation of physical objects is frequently utilized by science teachers when they asked their students to touch or "feel" certain physical objects (e.g., specimen, rocks) or phenomena (e.g., force, acceleration, heat). In the next example from another physics classroom in Singapore, a class of grade 9 students was involved in an activity to generate and describe the motion of a longitudinal wave motion using a slinky coil. Before the activity by each pair of students, the teacher first demonstrated the actions required to produce a pulse in the wave motion. He asked a student volunteer to hold on to one end of the coil while he pushed the other end to produce a pulse forward, as seen here:

Excerpt 4 (**bold** – material transitivity; <u>underline</u> – conjunction, *italics* – metadiscourse)

Line	Speaker	Spoken utterance	Gesture & Material Manipulation
1	Teacher	Okay. Let's say **I push**. Right, *you notice something*?	
2	Class	(Inaudible murmuring...)	
3	Teacher	*Observe that.* how **is it moving**...	
4	Teacher	<u>Then</u> the other **person holding** the other end. feels okay.	
5	Teacher	*Ask yourself how does it feel* alright. <u>when</u> it reaches the other end.	
6	Teacher	<u>Later</u>, *you can try* to increase speed.	
7	Teacher	<u>And</u> *see* how is it different...	
8	Teacher	(Gives instruction to carry out pair activity...)	
9	Teacher	One **person holds**, the **other person pushes**. <u>Then</u> change over.	
10	Teacher	Alright, <u>so</u> both have a feel	

In this excerpt, the teacher was verbalizing the material actions involved in the interaction with the slinky coil (e.g. *push* in line 1, *moving* in line 3, *hold* in line 4). This was similar to excerpt 1 when we discussed the role of objects as actualizing the material processes expressed in our verbal language. What is more relevant for our analysis here was his frequent instruction for the students to notice (line 1), observe (line 3), and importantly, *feel* (line 4, 5 & 10) the traveling pulse. In the teacher's demonstration, only one student could feel the pulse produced by the teacher. However, for the later pair activity, an instruction was given for one student to hold on one end while another student pushed from the other end (line 9). They were subsequently asked to swap their roles. This was to ensure that both students could "have a feel" (line 10) of the resulting pulse.

After the hands-on activity, each student was asked to record their observation (including their feeling) on a worksheet. In one of the worksheets, a student described not only the "wave sent" from the opposite end based on her sight, but also her sensation from holding the coil. For instance, she described she could "feel the force" and "the coils being pushed together." In a subsequent class discussion, the students' sensation were subsequently discussed. Notably, their physical sensations were transformed by the teacher into an experiential evidence for the forward propagation of mechanical energy in a wave motion.

Discussion of Findings

The findings in this study showed how physical objects as a semiotic mode have several crucial and unique affordances in mediating students' meaning-making in situ, in relation to verbal language and gestures. Thus, the material mode is not merely an auxiliary tool that substitutes teacher talk, caters to student interest, or supports emerging language learners as reported in previous literature (e.g., Buxton, 2006; Holstermann et al., 2010; Ünsal et al., 2019). Instead, the material mode is an integral piece of science meaning-making, albeit with a different set of affordances. It should therefore be given equal emphasis in the analysis of meaning-making, as illustrated in this study.

An empirical investigation in this study reveals four specific affordances of physical objects: (a) enacting material interaction, (b) providing evidential meaning, (c) orientating 3D spatial meaning, and (d) sensitizing experiential meaning. Each of these affordances highlights a number of theoretical and pedagogical aspects related to the use of physical objects in science or science learning. First, the affordance of enacting material interaction plays an indispensable role in creating the desired phenomenon for meaning-making. Second, the social practice of coordinating physical objects with metadiscourse to construct empirical evidence gives rise to the affordance of providing evidential meaning. Third, the perspectival viewing and interaction in a 3D space (in contrast to a 2D surface) give rise to physical objects' affordance of orientating spatial meaning. Finally, the tactile sensation and haptic manipulation of physical objects create an affordance of sensitizing experiential meaning. For the purpose of illustration, we provide a different example to show each affordance in the findings (Excerpt 1 to 4). However, each example could also be used to point to more than one affordances in unison.

Besides the material-operational mode, the approach in this study also considers and analyzes the roles from the verbal-linguistic and gestural-kinesthetic modes that frequently accompany the use of physical objects. These modes have different semiotic affordances compared to the material-operational mode. For instance, the verbal mode has several crucial roles that complement the material mode by providing the affordances to make categorical distinctions (e.g., point A vs. point B, rich vs. poor) and rhetorical arguments through the use of conjunctions and question-answer moves. It also has a metadiscourse function that allows us to talk about our ongoing talk. At the same time, the gestural mode has a supporting performative, deictic, and iconic role. Performative gestures are always needed to handle or operate the physical objects in order to generate the phenomenon for observation; deictic gestures are used to connect an utterance to an object; and iconic gestures are used to mimic the actions involved in manipulating physical objects.

Significance & Implications

Many education researchers have argued for the usefulness of physical objects by theorizing its intrinsic material properties and measuring its perceived advantages through self-report surveys or interviews (e.g., Abrahams & Reiss, 2012; Kirk, 2015; Martin et al., 2014). Such theorization and investigation focus only on its material dimension, which is incomplete as it is also important to examine what people *actually* do with physical objects during various meaning-making situations. For example, it is a well-known belief that physical models are useful for exploring spatial ideas due its three-dimensional property (Kress et al., 2001). However, this intrinsic property alone does not make any difference to a learning situation unless people react to accommodate it (Pickering, 1995) when making meaning in a 3D space. Thus, meaning-making is always contingent and situated to our interaction with physical objects. This consideration of both the material and semiotic dimensions as well as the connection to meaning-making has implications to how researchers must consider the role of materiality in the use of physical objects.

One theoretical implication is the entanglement between the material and semiotic dimensions in a material-operational mode, which often conflates the phenomenon we observe from the meaning we make about the phenomenon. It is often difficult to distinguish the material and semiotic dimensions of a sign within a material-operational mode, as compared to other modes. For instance, the word "shadow" is a sign within the verbal mode. We can easily differentiate the materiality of this sign (i.e., as the ink on a paper or pixels on a screen) from the semiotic meaning represented by the sign. However, if we create a real shadow and use it as a representation of shadow, then we can see a complex entanglement as the material sign in this case (i.e. shadow) is both a representation and the phenomenon itself. This entanglement is particularly problematic in science education as science is essentially the study of the material world (Barad, 2007).

In resolving this entanglement issue, this study demonstrates a way to distinguish between the material and semiotic dimensions of the signs within a material-operational mode. The material dimension gives rise to the natural phenomenon that people can see, hear, touch, or smell while the semiotic dimension is based on the layer of meanings that people make with the signs. We made a clear distinction between these two dimensions in our analysis when we examined the performative aspect of creating a phenomenon with physical objects (e.g., a shadow), followed by a discourse analysis of the meanings that were made through a coordination of the utterances and gestures with the physical objects.

This study also has implications to what we mean by "hands-on" science. A hands-on activity is generally perceived to provide a direct and first-hand encounter to a natural phenomenon by manipulating the physical environment. There is a tendency to dichotomize "hands-on" and "minds-on" as two separate activities, with the earlier focusing on manual operation of physical objects and the later focusing on the ideas generated through the literacy tasks of talking, reading, writing, or drawing (Osborne, 2019). Based on this study, we show that the complex entanglement between the material and semiotic dimensions of physical objects blurs the line between the hands-on and minds-on dichotomy. The meanings we make with physical objects are never just "hands-on" in terms of manual operation and manipulation, but they are also "minds-on" based on the semiotic actions that we say and do in coordinating the semantic connections among the verbal-linguistic, gestural-kinesthetic and material-operational modes. This hands-on/minds-on dichotomy is an individualistic and mentalist notion that ignores the social and material aspects of meaning-making. From a multimodal perspective, manipulation of physical objects is not just hands-on, manual, or practical work. It also supports (minds-on) idea generation through its meaning-making affordances that complement other modes. Thus, it will be more productive to view physical manipulation as an integrated multimodal meaning-making unit, with a unique set of semiotic affordances as documented in this paper.

References

Abrahams, I., & Reiss, M. J. (2012). Practical work: Its effectiveness in primary and secondary schools in England. *Journal of Research in Science Teaching, 49*(8), 1035-1055. https://doi.org/https://doi.org/10.1002/tea.21036

Abrahams, I., & Saglam, M. (2010). A Study of Teachers' Views on Practical Work in Secondary Schools in England and Wales. *International Journal of Science Education, 32*(6), 753-768. https://doi.org/10.1080/09500690902777410

Antin, T. M. J., Constantine, N. A., & Hunt, G. (2015). Conflicting Discourses in Qualitative Research:The Search for Divergent Data within Cases. *Field Methods, 27*(3), 211-222. https://doi.org/10.1177/1525822x14549926

Baldry, A., & Thibault, P. J. (2006). *Multimodal transcription and text analysis*. Equinox Pub.

Barad, K. (2007). *Meeting the universe half-way: Quantum physics and the entanglement of matter and meaning*. Duke University Press.

Buxton, C. A., & Lee, O. (2014). English learners in science education. In N. G. Lederman & S. K. Abell (Eds.), *Handbook of research on science education* (Vol. II, pp. 204-222). Routledge.

Candlin, F. (2010). *Art, museums and touch*. University Press Manchester.

Chen, S. F., Chang, W. H., Lai, C. H., & Tsai, C. Y. (2014). A Comparison of Students' Approaches to Inquiry, Conceptual Learning, and Attitudes in Simulation-Based and Microcomputer-Based Laboratories [Article]. *Science Education, 98*(5), 905-935. https://doi.org/10.1002/sce.21126

Cranny-Francis, A. (2011). Semefulness: a social semiotics of touch. *Social Semiotics, 21*(4), 463-481. https://doi.org/10.1080/10350330.2011.591993

Danielsson, K. (2016). Modes and meaning in the classroom – the role of different semiotic resources to convey meaning in science classrooms. *Linguistics and Education, 35*, 88-99. https://doi.org/http://dx.doi.org/10.1016/j.linged.2016.07.005

Erickson, F. (1992). Ethnographic microanalysis of interaction. In M. D. LeCompte, W. Millroy, & J. Preissle (Eds.), *The handbook of qualitative research in education* (pp. 201–225). Academic Press.

Ge, Y.-P., Unsworth, L., Wang, K.-H., & Chang, H.-P. (2017). What Images Reveal: a Comparative Study of Science Images between Australian and Taiwanese Junior High School Textbooks [journal article]. *Research in Science Education*. Ge2017. https://doi.org/10.1007/s11165-016-9608-9

Givry, D., & Roth, W.-M. (2006). Toward a new conception of conceptions: Interplay of talk, gestures, and structures in the setting. *Journal of Research in Science Teaching, 43*(10), 1086-1109.

Halliday, M. A. K. (1978). *Language as social semiotic : the social interpretation of language and meaning*. Arnold.

Halliday, M. A. K. (1985). *An introduction to functional grammar*. Arnold.

Halliday, M. A. K., & Martin, J. R. (1993). *Writing science : literacy and discursive power*. University of Pittsburgh Press.

Hand, B., McDermott, M., & Prain, V. (2016). *Using multimodal representations to support learning in the science classroom*. Springer.

He, Q., & Forey, G. (2018). Meaning-Making in a Secondary Science Classroom: A Systemic Functional Multimodal Discourse Analysis. In K.-S. Tang & K. Danielsson (Eds.), *Global Developments in Literacy Research for Science Education* (pp. 183-202). Springer International Publishing. https://doi.org/10.1007/978-3-319-69197-8_12

Hetherington, L., Hardman, M., Noakes, J., & Wegerif, R. (2018). Making the case for a material-dialogic approach to science education. *Studies in Science Education, 54*(2), 141-176. https://doi.org/10.1080/03057267.2019.1598036

Holstermann, N., Grube, D., & Bögeholz, S. (2010). Hands-on Activities and Their Influence on Students' Interest. *Research in Science Education, 40*(5), 743-757. https://doi.org/10.1007/s11165-009-9142-0

Jakobson, B., Danielsson, K., Axelsson, M., & Uddling, J. (2018). Measuring time. Multilingual elementary school students' meaning-making in physics. In K. S. Tang & K. Danielsson (Eds.), *Global developments in literacy research for science education* (pp. 167-181). Springer. https://doi.org/10.1007/978-3-319-69197-8_1

Jones, M. G., Andre, T., Kubasko, D., Bokinsky, A., Tretter, T., Negishi, A., Taylor, R., & Superfine, R. (2004). Remote atomic force microscopy of microscopic organisms: Technological innovations for hands-on science with middle and high school students. *Science Education, 88*(1), 55-71. https://doi.org/10.1002/sce.10112

Jordan, B., & Henderson, A. (1995). Interaction analysis: Foundations and practice. *The journal of the learning sciences, 4*(1), 39-103.

Kirk, J. (2015). *Using manipulatives in the Chemisty classroom as a tool to increase the understanding and knowledge of the law of conversation of matter* St. John Fisher College]. Rochester, N.Y.

Kress, G. (2010). *Multimodality: A social semiotic approach to contemporary communication*. Routledge.

Kress, G., Jewitt, C., Ogborn, J., & Tsatsarelis, C. (2001). *Multimodal teaching and learning: the rhetorics of the science classroom*. London: Continuum.

Kress, G., & van Leeuwen, T. (2006). *Reading images : the grammar of visual design* (2nd edition ed.). Routledge.

Kuhn, T. S. (1962). *The structure of scientific revolutions*. University of Chicago Press.

Latour, B. (1987). *Science in action : how to follow scientists and engineers through society*. Harvard University Press.

Latour, B., & Woolgar, S. (1979). *Laboratory life: the construction of scientific facts*. Princeton University Press.

Lemke, J. L. (1990). *Talking science: language, learning and values*. Norwood, NJ: Ablex.

Lemke, J. L. (1998). Multiplying meaning: visual and verbal semiotics in scientific text. In J. Martin & R. Veel (Eds.), *Reading Science* (pp. 87-113). Routledge.

Lemke, J. L. (2003). Mathematics in the middle: Measure, picture, gesture, sign, and word. In M. Anderson (Ed.), *Educational perspectives on mathematics as semiosis: From thinking to interpreting to knowing* (pp. 215–234). Legas.

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

Lundqvist, E., Almqvist, J., & Östman, L. (2009). Epistemological norms and companion meanings in science classroom communication. *Science Education, 93*(5), 859-874. https://doi.org/10.1002/sce.20334

Martin, S. F., Shaw, E. L., & Daughenbaugh, L. (2014). Using Smart Boards and Manipulatives in the Elementary Science Classroom. *TechTrends, 58*(3), 90-96. https://doi.org/10.1007/s11528-014-0756-3

Martinec, R. (2000). Types of process in action. *Semiotica, 130*(3-4), 243-268.

Milne, C., & Scantlebury, K. (Eds.). (2019). *Material Practice and Materiality: Too Long Ignored in Science Education*. Springer.

Mitchell, J. C. (1983). Case and situation analysis. *Sociological Review, 31*, 187-211.

Moro, L., Mortimer, E. F., & Tiberghien, A. (2020). The use of social semiotic multimodality and joint action theory to describe teaching practices: two cases studies with experienced teachers. *Classroom Discourse, 11*(3), 229-251. https://doi.org/10.1080/19463014.2019.1570528

O'Halloran, K. L. (2000). Classroom discourse in mathematics: A multisemiotic analysis. *Linguistics and Education, 10*(3), 359-388.

Olohan, M. (2016). Science, Translation and the Mangle: A Performative Conceptualization of Scientific Translation. *Meta, 61*, 5-21. https://doi.org/https://doi.org/10.7202/1038682ar

Osborne, J. F. (2019). Not "hands on" but "minds on": A response to Furtak and Penuel. *Science Education, 103*(5), 1280-1283. https://doi.org/10.1002/sce.21543

Peirce, C. S. (1986). *Writings of Charles S. Peirce : a chronological edition*. Indiana University Press.

Perin, S. M., Carsten Conner, L. D., & Oxtoby, L. E. (2019). How various material resources facilitate science identity work for girls in a research apprenticeship program. *Journal of Geoscience Education*, 1-11. https://doi.org/10.1080/10899995.2019.1700594

Pickering, A. (1995). *The mangle of practice: Time, agency, and science*. University of Chicago Press.

Roehl, T. (2012). From witnessing to recording – material objects and the epistemic configuration of science classes. *Pedagogy, Culture & Society, 20*(1), 49-70. https://doi.org/10.1080/14681366.2012.649415

Roth, W. M. (1999). Discourse and agency in school science laboratories. *Discourse Processes, 28*(1), 27-60.

Sørensen, E. (2009). *The materiality of learning: Technology and knowledge in educational practice*. Cambridge University Press.

Stake, R. E. (2000). Case studies. In N. Denzin & Y. Lincoln (Eds.), *Handbook of qualitative research* (2nd ed., pp. 435-454). Sage.

Tang, K. S. (2017). Analyzing teachers' use of metadiscourse: The missing element in classroom discourse analysis. *Science Education, 101*(4), 548-583. https://doi.org/10.1002/sce.21275

Tang, K. S. (2020). *Discourse Strategies for Science Teaching and Learning: Research and Practice*. Routledge.

Tang, K. S., Delgado, C., & Moje, E. B. (2014). An integrative framework for the analysis of multiple and multimodal representations for meaning-making in science education. *Science Education, 98*(2), 305-326. https://doi.org/10.1002/sce.21099

Tang, K. S., Won, M., & Treagust, D. F. (2019). Analytical Framework for Student-Generated Drawings *International Journal of Science Education*. https://doi.org/10.1080/09500693.2019.1672906

Ünsal, Z., Jakobson, B., Wickman, P.-O., & Molander, B.-O. (2019). Jumping pepper and electrons in the shoe: using physical artefacts in a multilingual science class. *International Journal of Science Education*, 1-20. https://doi.org/10.1080/09500693.2019.1650399

Van Rooy, W. S., & Chan, E. (2017). Multimodal representations in senior biology assessments: A case study of NSW Australia. *International Journal of Science and Mathematics Education, 15*(7), 1237-1256. https://doi.org/10.1007/s10763-016-9741-y

Vande Kopple, W. J. (2012). The importance of studying metadiscourse. *Applied Research on English Language, 1*(2), 37-44.

Varelas, M., Pieper, L., Arsenault, A., Pappas, C. C., & Keblawe-Shamah, N. (2014). How science texts and hands-on explorations facilitate meaning making: Learning from Latina/o third graders. *Journal of Research in Science Teaching, 51*(10), 1246-1274. https://doi.org/10.1002/tea.21173

Weinstein, M. (2010). The materiality of learning: Technology and knowledge in educational practice. *Science Education, 94*(6), 1123-1125. https://doi.org/10.1002/sce.20406

Williams, M., & Tang, K. S. (2020). The implications of the non-linguistic modes of meaning for language learners in science: a review. *International Journal of Science Education*. https://doi.org/10.1080/09500693.2020.1748249

Wu, S. C., Silveus, A., Vasquez, S., Biffi, D., Silva, C., & Weinburgh, M. (2019). Supporting ELLs' Use of Hybrid Language and Argumentation During Science Instruction.

Journal of Science Teacher Education, 30(1), 24-43. https://doi.org/10.1080/1046560X.2018.1529520