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GRAVITY, IMAGINATION AND EMBODIED CONCEPTIONS OF SPACETIME

Magdalena Kersting[1], *Rolf Steier* [2]
[1]Department of Physics, University of Oslo, Norway
[2] Department of Education, University of Oslo, Norway

Though we live in a four-dimensional universe, our minds and bodies are not particularly good at perceiving and depicting four dimensions. In this study, we use upper secondary physics classrooms studying Einstein's general theory of relativity as a setting to identify conceptual challenges and representational practices that arise when learners attempt to make meaning with, and express conflicting notions of, gravity, space and time. Specifically, this study contributes to our understanding of imaginative strategies that learners employ to make sense of gravity when bodily and experiential understandings conflict with the conceptual domain. Building on theoretical perspectives that treat imagining as a social activity, we carry out a detailed analysis of an extended conversation between two upper secondary physics students working with concepts of gravity. We demonstrate that students perform a diverse set of imaginative strategies that are strongly tied to cognitive, communicative, and bodily practices when trying to relate abstract descriptions of curved spacetime to their everyday experience of gravity. Based on our analysis, we give recommendations to improve instructional practices in general relativity and argue for the consideration of imagining as an important competency in science education.

Keywords: General Relativity, Gravity, Imagination

INTRODUCTION AND THEORY

Introducing the idea that gravity is not a force, but a manifestation of the geometry of the universe, Einstein set the stage for modern physics. Whereas time and space are static features in classical physics, general relativity (GR) merges time and space into a dynamic four-dimensional fabric called "spacetime". Gravity is interpreted geometrically as the curvature of spacetime.

Even though studies have focused on identifying and overcoming learners' difficulties with key concepts in GR (Bandyopadhyay & Kumar, 2010; Velentzas & Halkia, 2013), hardly any educational research deals with students' understanding of gravity as curvature, an exception being Pitts et al.'s (2014) study of year 6 students. Given that relativistic phenomena contradict learners' experiences and deeply rooted knowledge from classical physics, studying meaning making processes on gravity can show how learners might reconcile Einstein's abstract description with their classical and experiential understanding of gravity.

Since science often deals with the unobservable, such as four-dimensional spacetime, imagination plays a crucial role in science practice and education (Hadzigeorgiou, 2016). We argue that GR provides a rich setting to study imaginative processes in physics classrooms that can shed light on learners' understanding of gravity. Building on theoretical positions that treat imagining as a socially situated activity, we address the following research questions: 1) What imaginative strategies do students use to communicate and make sense of gravity and spacetime? 2) How are these imaginative processes performed? To address these questions, we apply a perspective of embodied interaction (Streeck, J., Goodwin & LeBaron, 2011) and place gestures at the centre of our analysis.

METHOD

This study has been conducted within the design-based research project ReleQuant that develops online learning modules in modern physics (Henriksen et al., 2014). ReleQuant emphasizes qualitative and philosophical aspects of modern physics and is based on a sociocultural view of learning. The learning module on GR was introduced to students (18-19 years) in six Norwegian upper secondary physics classes in 2016. Teaching comprised two 90-minute units and was conducted by the regular physics teachers.

This study is based on video recordings; secondary data include student texts, audio recordings, and field notes. Our interest in gravity related to processes of imagining led us to identify segments of video data in which students were working explicitly with the concepts of curvature and spacetime. These excerpts were transcribed and translated from Norwegian, and analysed using interaction analysis methods (Jordan & Henderson, 1995) with attention to the bodily and material practices of participants (Streeck, J., Goodwin & LeBaron, 2011). We focused on the turn-by-turn sequencing of utterances in relation to bodily and gestural practices, as well as orientations to material resources (computers, texts, etc.). The supplementary data allowed us to interpret interactions in the context of the cultural and institutional practices of the science classrooms. We selected one rich episode to focus on for this study, involving one pair of notably engaged students, as illustrative of imaginative processes. This pair was thus not representative of broader classroom patterns, but their deep engagement gives us insight into their processes of meaning making of gravity.

RESULTS

In the episode, 'Ben' and 'Sam' have completed the spacetime unit, but they struggle to accept aspects of the new concepts. The conversation consists of Ben trying to articulate his confusion, followed by Sam attempting various strategies to explain his understanding of spacetime. Between these attempts, Sam often notes that Ben "cannot imagine" the thing that he is trying to understand and must just "accept" it.

This episode reveals a complex and diverse set of representational and imaginative strategies to deal with spacetime performed by Ben and Sam, and importantly, that these strategies are closely linked to their bodily practices. In a series of turns, Sam's hand depicts a physical slope, an abstract curved line, the curvature of spacetime itself, and an imaginary ball being placed on a slope. Ben seems to be struggling to conceptualize the notion of spacetime and attempts to draw spacetime, but this quickly becomes problematic revealing a close relationship between his visualizing, imagining, and understanding of the concept. He shifts across several modalities, including the use of language, drawing, textbook, and imagined scenarios. In probing various imaginative strategies, the pair constructs their own thought experiments: They place themselves in orbits around the sun and follow the movement of an imaginary ball on a slope.

Throughout the conversation, Ben attempts to align the theory of gravity with his earlier understandings about gravity as a force that pulls. He wonders how gravity in the form of curvature can pull or make objects fall, when an object is at rest. The episode thus reveals that for Ben curvature is closely related to movement.

Sam: *I think that as such, sort of the straight space is deflected, so when the particle goes straight then it really doesn't go straight, because the space is bent over ((Sam extends his right hand with palm facing downwards and then tracing a path with his left index finge.r))*
Ben: *But, when you stand still.*
Sam: *Yes.*
Ben: *So it will not help me (with) why you then still fall.*
Sam: *No, no, but you fall all the time, even when you are standing on Earth, it's just that there is resistance up again ((points up with his right hand)). So you're still falling, you're like falling all the time.*
Ben: *Yes, but it's hard to understand that you fall without a gravitational force. But only with curvature.*

This insight that one is always in a sense 'falling' through spacetime is perhaps the key insight that Ben has not acknowledged and that Sam has perhaps not clearly articulated.

DISCUSSION AND CONCLUSION

Identifying practices of imaginative reasoning in GR gives clues on how to improve teaching and learning of gravity and spacetime. Ben has just learned that gravity stems from curvature. While he uses this explanation to understand orbital motion, he struggles with his conclusion that the same must hold true for his own body. He cannot overcome his experiential understanding of gravity as a force and cannot fully accept that he experiences gravity because spacetime is curved. Since the presentation of gravity in the learning module relied on moving objects, it is natural that Ben wonders how gravity works for an object at rest. He does not realize that we are moving along the time-dimension as well. Ben's struggle could be resolved by explaining that objects continually move in spacetime. We suggest that thought experiments on movement in time could serve as suitable instructional tools to tackle challenges in meaning making processes of GR, thus extending findings of Velentza et al. (2013) on thought experiments in relativity.

Moreover, we observe that students make gestural inferences about spacetime that seem to obscure deeper understanding. Scherr (2008) emphasizes how gestures provide sensorimotor information that prompt idea construction. However, this feature of embodiment might run into conflict with the abstract domain of GR. The challenge is that our sensory experiences of gravity may actually *contradict* the concept of spacetime. Because such imaginative strategies are emergent without instructional consideration, there is potential for conflict when these practices do not transfer across new conceptual domains. Moving from Newtonian to Einsteinian physics presents one example where the ways that students use imaginative activities as conceptual mediators may be problematic. We argue that imagining should be an explicit part of instruction – both in specific contexts like GR, but more importantly as a process that can be applied across learning domains. Developing instructional opportunities for students to engage in imaginative processes thus opens up new possibilities for students to engage with mathematical and scientific practices.

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