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Up and down, light and heavy, fast and slow—but where?

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Abstract

Vertical amusement rides let your body experience the tickling sensation of feeling light, but also feeling much heavier than as usual, due to velocity changes as you move up and down. Family rides offer different possibilities to visualize the forces that are experienced by your accelerating body. This paper presents a number of different ways to view and experience the motion in a small vertical amusement ride. A smartphone includes an accelerometer that can provide a graph of the forces acting during the ride. A movie from the smartphone camera lets students recall the motion which can then be analysed in more detail. The complementary representations may help students develop a deeper understanding of the relation between force and motion. The affordances of these different semiotic resources are analysed in some detail. In addition, we discuss responses from a number of students to questions about where you feel light and where you feel heavy. We find that the experience of the body is an underused resource in physics teaching.

1. Introduction

Acceleration is often viewed as abstract, but when a person accelerates, e.g. in a car or on swings, trampolines, carousels or rollercoasters, the force required for the acceleration is felt throughout the body [1]. Student difficulties in understanding force concepts are very well documented in physics education research (see e.g. [2]). If acceleration is introduced as force divided by mass rather than as a second derivative of displacement, the concept can be made accessible to much younger

learners, such as 10 year olds taking part in supervised visits to an amusement park or playground [1]. The force required for acceleration can be measured e.g. using smartphone sensors. A small slinky can also be used for visual demonstrations that complement photos and video analysis. For a teacher this creates opportunities to discuss challenging concepts of force and motion, in enjoyable authentic situations.

Vertical amusement rides are popular in physics teaching. Forces and motion are then in the same—or opposite—direction. In this paper we present a number of different representations of the motion in a Family Free Fall Tower (figures 1 and 2) from Zierer (www.zierer.com). However, the understanding that students construct from such experiments and exercises is not well known.



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Figure 1. Examples of Familien FreiFallTurm: Stjernetårnet at Tivoli Gardens, Lyktan at Gröna Lund and Hissningen at Liseberg. Some of the riders in Lyktan hold short slinkies illustrating the forces acting on the body.

Therefore, we are investigating students ideas and conceptions concerning the connection between the theoretical concepts velocity, accelerations and force and the embodied experience of accelerating as they move up and down.

2. The language of physics

The Book of Nature is written in the language of mathematics according to Galileo. Indeed, the study of motion rests to a large extent on mathematics, as discussed in section 3. The language of physics includes many additional semiotic resources (see below) that can be regarded as part of a *language* in a broader sense, including text, mathematics, programming, simulations, gestures, as well as diagrams and graphs [3]. Here, we are particularly interested in how students connect the bodily experience to graphs and mathematical expressions. The equations of motion may be studied in connection e.g. with free-body diagrams and with st and vt graphs showing how distance and velocity varies with time, as well as simulations and demonstrations of the motion of physical objects. Learning physics then also involves learning to read and write the language of physics, and to understand the intended meaning of these discipline-specific semiotic resources

[4, 5]. In this work we aim to support the connection between the free-body diagram description of the upward force from the seat acting on your body with the experiences of feeling heavy or light due to acceleration—i.e. the perceived weight—during different parts of the motion.

2.1. Semiotic resources in physics education

Semiotic resources are commonly divided into *representations, tools and activities* and these are used to communicate knowledge within a discipline, such as physics [3].

The resources used in textbooks to describe motion are often a limited subset of the language of physics. The treatment typically starts from a *representation* in the form of kinematic equations, where forces are not included. In upper-secondary textbooks, as well as in introductory university textbooks, Newton's laws are traditionally introduced after several chapters dealing with kinematics.

Free-body diagrams can be seen as a *tool* for understanding motion in different situations. Forces in the textbook free-body diagrams typically act on rectangles or boxes—the textbook 'bodies' are rarely human. If forces acting on a human body are mentioned, it is likely to be in

connection with an elevator, but focusing more on the reading of a bathroom scale than on the experience of the body.

Experiments are also a standard *activity* in physics education: the study of motion can involve carts on track, that may be accompanied by ticker tape or short videos of special motion situations, as in Live Video Physics (www.rit.edu/cos/livephoto/). Students may also have used the opportunities for video analysis provided e.g. by Tracker (www.physlets.org/tracker) and perform electronic data collection using wireless sensors, e.g. from Vernier (www.vernier.com) or Pasco (www.pasco.com) or smartphones [6, 7]. However, experiments involving forces on students' own body are rarely seen in textbooks.

Learning physics can be regarded as coming to appreciate and use the traditional resources and move between them, as well as connecting them to the experience itself. This is known to be difficult but also important for building a deeper understanding [8]. It is, for example, found that gestures can work as an effective means to move between different semiotic resources [9, 10]. Such semiotic resources then work as *transductive links* between other semiotic resources [11]. To find these transductive links thus becomes an important task for the educator. Here, we are interested in how the bodily experience can work as such link, and contribute to constructing a deeper understanding of the phenomena at hand.

The importance of bodily experiences was introduced in early theories on learning. For example, John Dewey [12], followed by Kolb [13], described 'a process by which hands-on opportunities in an active learning environment drive knowledge. However, the specific mechanism through which this process occurs has not been well defined' [14]. The idea is that our disciplinary-specific representations of a concept, such as acceleration and force, can be seen as grounded in perceptual, somatosensory, and motoric re-experiencing of relevant events in one's own body [15]. In the research literature, high degrees of knowledge and skills often are associated with embodied experiences ('embodiment') [16–19], highlight the power of embodied experiences for physics learning. They seem to have the power to work as a transductive link between other resources that are used to describe a physical phenomenon. The literature shows that

there are two sides to the coin; on one hand we find that the *embodied experience* helps to build knowledge about a concept and, on the other hand, *gestures* work as a means to describe and explain the experience. However, this is not well explored in the physics education research (PER) literature and thus deserves more attention.

2.2. Unconventional semiotic resources—in the amusement park

This paper explores a number of unconventional semiotic resources, in connection with the Family Free Fall amusement ride. For students visiting the park, the *activity* of riding the tower and experiencing the motion and the forces on (and within) one's body can be regarded as a semiotic resource. However, most people who visit an amusement park do not connect the experience to more traditional physics descriptions of motion, nor to the language we use, including gestures, mathematics, graphs and diagrams to describe the experience.

2.3. The slinky—a small plastic spiral to measure acceleration

For many years, participants in amusement park physics days have been invited to take along a short slinky on a rubber band (figure 3) in small drop tower rides and observe how the slinky changes length during the motion [1]. We have found that during the visits most students need some scaffolding questions from a teacher or a guide to make the connection between the length of the slinky, the part of the ride and the sensation of the body. During their first ride, students are often too excited to observe the slinky while also paying attention to the experience of the body. Riding a second time can help students make this connection and also relate their observations to the different parts of the motion. Viewing someone else ride with a slinky helps students combine the experiences during the ride with the more traditional external view of motion. With scaffolding, the slinky can thus function as a *tool* for illustrating the forces on the body, helping students to move between different representations.

2.3.1. Slinkies and electronic accelerometers.

The varying distance between the coils of the slinky can also serve as an illustration of the

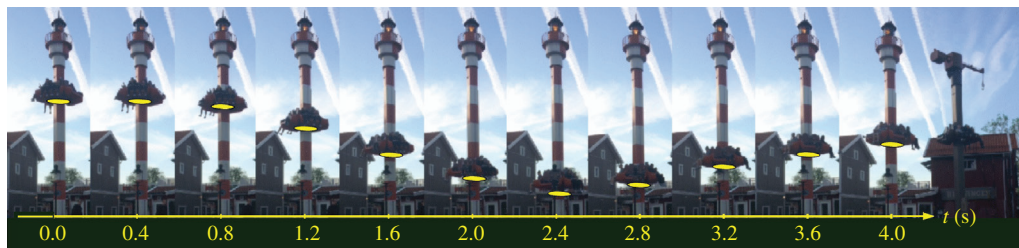


Figure 2. A sequence of screenshots for the Familien FreiFallTurm Hissningen at Liseberg. The red and white fields are 1.1 m high, providing a vertical scale.

work of electronic accelerometers, where the distance between small capacitor plates vary with the acceleration, e.g. in Smartphones. Figure 4 shows electronic accelerometer data collected in a Family Free Fall Tower, indicating that the force from the seat on the riders varies between approximately half and double its normal value mg . This corresponds to a slinky length between half and double its normal length. (More precisely, if the length of the slinky is l_0 when in free fall or resting on its side and l_1 when it is hanging at rest, the length during the ride will vary between $(l_0 + l_1)/2$ and $2l_1 - l_0$.)

2.4. Screen shots of the motion viewed from outside

The sequence of screen shots shown in figure 2, giving a graphical *representation* of the motion, was created as an instrument to probe students' ability to discern the concepts of elevation, velocity and acceleration in one dimension and to connect acceleration to force. We also developed a few additional representations as discussed in section 3. We hoped that the sequence could also evoke memories from earlier rides.

2.5. Research questions

Based on the above theoretical framework and the hypothesis that students understand physics better when experiencing it with their own bodies, our research questions are:

- How do students connect different disciplinary-specific representations to their embodied experience before, during and, after a ride?
- How can unconventional semiotic resources act as transductive links between more conventional descriptions of force and motion?

To address these questions, we invited students to participate in our study during a 'Physics Day' in a large amusement park in Sweden. The participant students were interviewed before the vertical ride, and afterwards, about their thought about how it would feel at different moments during the ride, and how they thought it would feel in their bodies. Afterwards, similar questions were asked and in particular questions regarding their embodied experience of the ride. In addition, written responses were collected from several groups. The results are presented in section 4. As a background, we first provide a mathematical representation of the motion of the ride, based on observations and measurements made by the authors.

3. Mathematical representations of motion

Lower secondary students (age 13–16) are likely recognize the relation $s = vt$, for motion in one dimension and with constant velocity. Possibly, they also recall the relation $v = gt$ for an object in free fall, starting from rest. Their more complex everyday motions in three dimensions are often not discussed in school.

In upper secondary school, students will encounter derivatives, at least for motion in one dimension, e.g. $v = ds/dt$, and $a = dv/dt$. Although the relations may be introduced through graphical representations of an arbitrary motion, the focus in the exercises is more often on applying 'the kinematic equations' for constant acceleration as well as using formulae for a few other special cases, including projectiles and circular motion. The use of mathematics to describe motion, of course, goes beyond these special cases. The underlying relations between displacement, velocity and acceleration, using derivatives

and integrals, can be applied to general motion in three dimensions.

Figure 2 is a sequence of screenshots from a movie of the one-dimensional motion of the ride Hissningen at Liseberg, showing the elevation, h of the gondola at different times. This sequence can be used as a basis for a discussion of velocities, acceleration and the experience of the body. The changes in elevation, Δh , between consecutive screenshots indicate the size and direction of the average velocity between these images. This can be used to remind students of the definition of the derivative.

$$v = \frac{dh}{dt} = \lim_{\Delta t \rightarrow 0} \frac{\Delta h}{\Delta t}.$$

A visual inspection of the sequence indicates a relatively constant downward velocity in the interval 1.2 s–2.0 s and a relatively constant, but slightly smaller, upward velocity between 3.2 s and 4.0 s. The changes in elevation have been marked with red arrows in figure 5. A constant velocity requires the sum of the forces on the body to be zero, and the rider then experiences ‘1g’, corresponding an upward ‘normal force’ from the ride, with the size mg .

The sequence of screen shots in figure 2 and the subsequent graph in figure 5 provide *representations* that can be seen as semiotic resources. At the same time, drawing the change in elevation (with length proportional to the average velocity) can be seen as a possible *activity* for students, intended to facilitate the connections between the real-life experience and the formal definition of velocity. The sequence of screen shots can thus also be considered as a *tool* enabling this activity.

3.1. Acceleration, force and the second derivative of elevation

Just before and after the lowest and highest points, the ‘velocity’ arrows are much shorter. The change in velocity arrow lengths, marked with blue arrows figure 6, are a ‘second difference’ giving the change in average changes in displacement, $\Delta(\Delta h)$, indicating acceleration. Recall

$$a = \frac{dv}{dt} = \frac{d^2h}{dt^2}$$

which can be approximated with

$$a \approx \frac{\Delta v}{\Delta t} \approx \frac{\Delta(\Delta h)}{(\Delta t)^2}.$$

From this exercise it is clear that the maximum upward acceleration is at 2.4 s and the maximum downward acceleration is at 0.8 s in figure 2.

3.2. From derivatives to integrals

Acceleration is not only a second derivative of location, but also related to force through Newton’s second law, $\mathbf{a} = \mathbf{F}/m$. Figure 7 illustrates the normal force (i.e. the upward force from the seat) on the rider for the different parts of the bounce, required for the accelerations illustrated in figure 6. These varying forces are experienced in the body of the riders and can also be measured, e.g. with smartphone sensors and illustrated with a short slinky.

In spite of its name, an accelerometer does not measure acceleration, but the forces other than gravity acting on a body, expressed in terms of the vector $\mathbf{a} - \mathbf{g}$, or a ‘g force’ or ‘g factor’, $(\mathbf{a} - \mathbf{g})/g$, which has the value 0 in free fall and the size 1 for bodies at rest or in uniform rectilinear motion (with components depending on the orientation of the accelerometer). In the case of Hissningen, the only force counteracting gravity is a normal force N and the output from the accelerometer can be expressed as N/mg . The function of an accelerometer can be illustrated with a slinky taken along during the ride, which also provides a realtime visual measurement to enhance the experience of the body.

Figure 4 shows accelerometer data for the whole ride in a Family free fall tower. The screenshots shown in figure 2 corresponds to one of the first large bounces. Velocities and elevations during the ride can be obtained by numerical integration of the acceleration values, e.g. as

$$v_n = v_0 + \Delta t \sum_{i=0}^{n-1} a_i$$

and

$$h_n = h_0 + \Delta t \sum_{i=0}^{n-1} v_i.$$

The resulting velocities and elevations for two bounces are shown in figure 8.

It may be necessary to add small correction terms, $a_{corr}(t - t_0)$ to the velocity expression to ensure that the velocity and elevation at the end of the interval are realistic. In addition, if the accelerometer was not kept perfectly vertical during the ride, the values for the vertical acceleration will be underestimated and a scale factor can be included if the elevation differences turns out to be too small. In this context, it is useful to bring uncertainties in the sensor data to students' attention, including a discussing of calibration and resolution. For example: ask students to estimate the effect on velocity and elevation after 80 s of a small error in the acceleration, comparable to the resolution of the sensor.

4. Data collection

The screen shot sequence in figure 2 of the vertical ride 'Hissningen' was created as part of the preparations for a Physics Day at Liseberg in 2017 for students aged 12–19, as a complement to assignments involving a slinky. Prior to the physics day, the sequence of screen shots had also been tried during teacher workshops—although without access to the ride.

Figure 2 was used as part of discussions with students visiting the Hissningen ride, where they also had the opportunity to ride with a slinky, and to observe how its length changed during the ride.

Complementary data were obtained by including questions about the screen shot sequence as part of the test used for selections to the national final of the European Union Science Olympiad, EUSO for 16–17 year olds. (N.B. Each school could send responses from up to three students for selection to the Swedish final.)

5. Results

Below, we first present the results from the groups who responded without access to the ride, where any use of the experience of the body was through previous experiences. We then present, in some detail, responses from small-group interviews.

5.1. Teacher workshops

On a few occasions, the screen shot sequence in figure 2 has been used for small-group discussions

as part of a teacher workshop. Typically, the teachers would then first note that the ride moves faster on the way down than on the way up. Physics teachers for upper-secondary school then usually note that the curvature or deviation from a straight line indicates acceleration. The connection to the apparent weight then follows after working out the direction of the acceleration.

Teachers who are teaching all sciences in lower-secondary school may need some scaffolding to discuss acceleration and often need to be reminded of the difference between velocity, \mathbf{v} , and speed, $|\mathbf{v}|$. The discussion can be supported by a demonstration where a slinky is moved up and down, which can be a connection to the experience of the body. In addition, a movie with a rider carrying a slinky in a similar ride, as shown e.g. in the video abstract, can help making the connection to the real-life motion (See also figure 3).

5.2. EUSO test 2017

Figure 9 shows responses from submissions to the selection for participants in the the Swedish final (for 15–16 year olds) for the European Union Science Olympiad (EUSO). The responses show a relatively good consensus that the highest speed is around 1.2 s and that the slowest motion is around 0.4 s and/or 2.4 s. Some students reported that you move faster on the way down than on the way up in this ride.

As a complement the students were also asked to describe how they thought riding would feel. Many students briefly state 'You feel heavy as you go up and very light as you move down'. A few students talk about varying G forces relating to the feeling of light and heavy.

Many students referred to a tickling sensation. Some were more specific, adding 'on the way down' (and a single response stated 'on the way up'). One response mentions weightlessness and elaborates 'but what you feel is inertia, when it feels like your body cannot keep up'. Another student describes an experience of falling 'like if you are going to hit the ground'.

A few responses related to the experience in a car, e.g. that you are lifted and then pushed down a number of times, like when travelling over a bumpy road.



Figure 3. A slinky used to visualize the forces on the rider in different parts of the Stjernetårnet Family free fall tower at Tivoli Gardens.

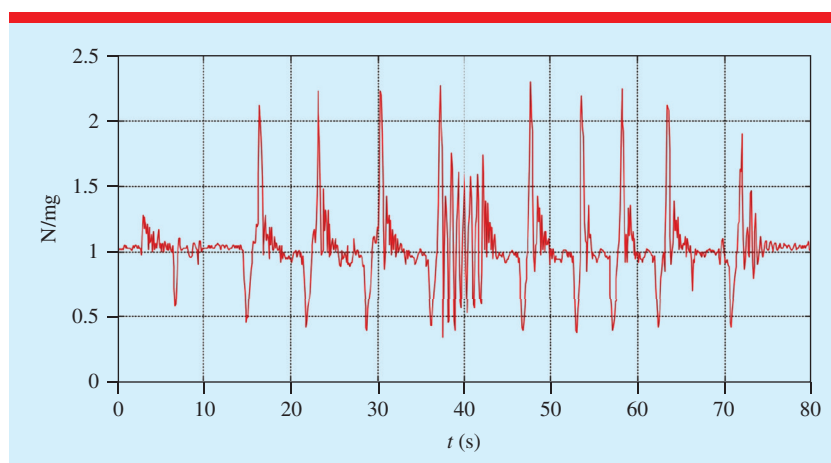


Figure 4. Accelerometer data from a ride in Hissningen. Note the difference in time on the horizontal axis from figure 2.

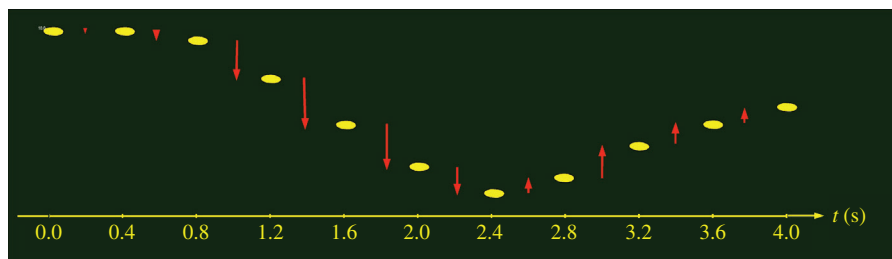


Figure 5. Change in elevation, Δh , between two consecutive screenshots (figure 2), indicating average velocity in that interval.

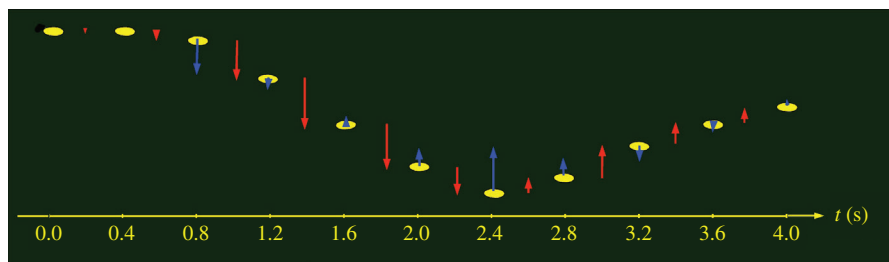


Figure 6. Change in average changes in displacement, $\Delta(\Delta h)$, between two consecutive intervals shown in figure 5. The length of the blue arrows is proportional to the acceleration.

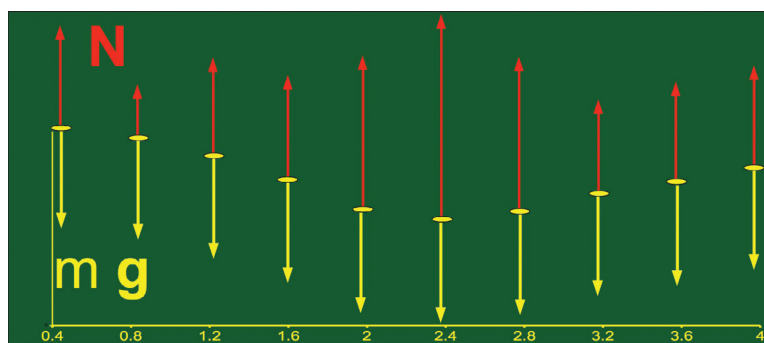


Figure 7. Normal force on the rider, extracted from the accelerations in figure 5.

5.3. Interviews next to the ride

During the Physics Day at Liseberg 2017 for students aged 12–18, 25 groups of 3–5 students were interviewed before and after the ride. The groups were asked about during which parts of the ride they would feel the lightest and where they would feel the heaviest, and about force and acceleration in different points. In addition to the series of screen shots (figure 2), the students could also use plastic springs (slinkies) as spring balances (figure 3) to investigate how different types of motion changes the apparent weight.

5.3.1. 12–15 year olds. The first few groups were 12–15 year olds from several schools in west Sweden. Before riding, they were uncertain about what to expect, often noting that ‘We have not thought about that’, or ‘I do not know’. After some discussions within the groups, most students concluded that one probably felt the heaviest at the bottom, ‘after the free fall’ when the ‘lift’ turns. A few students expressed that maybe one felt heavier just before or after reaching the lowest point.

The question about where you feel the lightest was found to give more divergent views.

Students guessed at various positions in the upper part of the motion. A common response was students expressing that you would not feel anything special (not accelerating) in the highest point, whether moving up and then directly down again, or if first stopping at the highest point.

After the ride, these students were all convinced that you felt the heaviest at the bottom. Many of them had also noted that the slinky was the longest at the bottom, confirming their hypothesis. After the ride, many also reported that they felt lighter in the highest points around 0.4 s–0.8 s in figure 2). Some of the students had also noted that the slinky was shorter already before they reached the highest point and not only just after the highest point. This surprised many of them, as they did not seem to expect that; textbook discussions of acceleration during a fall typically only involve moving downwards.

Many students also mentioned that the force and acceleration was upwards on the way up, and downward on the way down—not yet distinguishing acceleration from velocity.

5.3.2. 16–19 year olds. Relatively few students older than 15 chose the Family Free Fall ride and

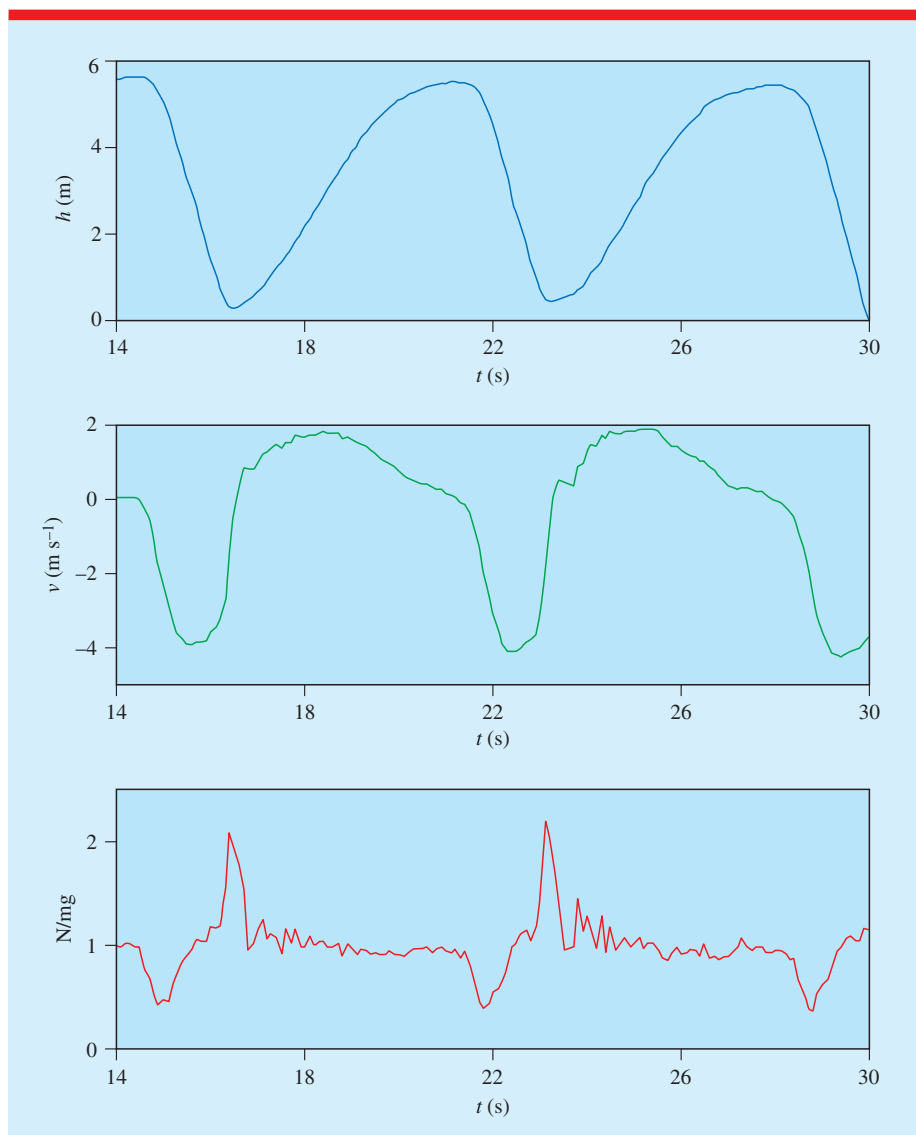


Figure 8. Elevation and velocity during the first bounces, obtained by numerical integration of the accelerometer data.

only one group of 5 students was interviewed. Initially, they were convinced—like the younger students—that you would feel heaviest at the bottom, while being more uncertain about where you would feel the lightest ‘It ought to be at the highest point, I think, but maybe just before or after’ often followed by ‘I have to do some calculations’. The group also stated that the acceleration, as well as the force, was largest at the bottom, whereas the question about where there was least force caused more difficulties. The group started to talk about

writing down a formula and do some calculations, but were generally unwilling to discuss of the experience itself. They wanted to calculate!

After the ride, they remained convinced that they were heaviest at the bottom, which was also where the acceleration and the force would be largest. They were unsure whether the ride involved a free fall or not, and how this would influence the experience and the observation of the slinky. This was a kind of observation and comment that the younger students did not report upon, and of

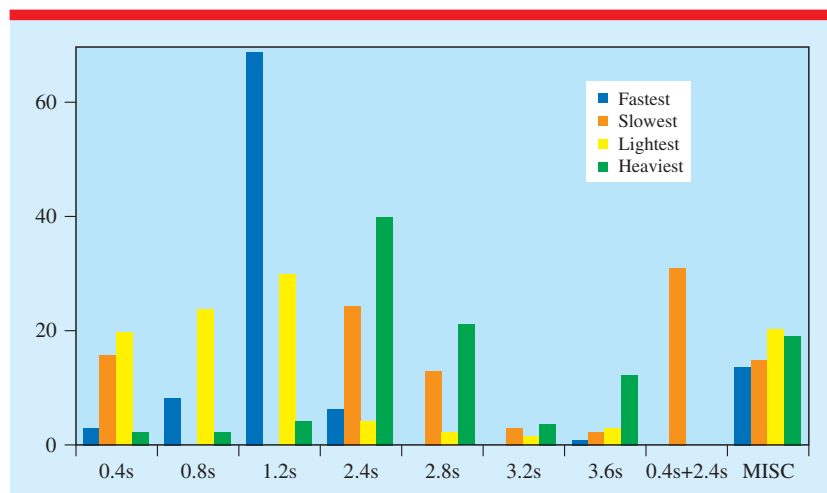


Figure 9. When do you move fastest and slowest and when you feel lightest and heaviest during the sequence of screenshots shown in figure 2? Percentages of different responses from a total of 148 respondents from the Swedish EUSO selection test for 15 and 16 year olds.

course they are correct in this observation; it is unlikely that there is a true free fall on the way up to the highest point. However, they reported that ‘probably, there was a free fall period just after the highest point, but it was difficult to observe, experience...’. They also found that it was difficult to be certain about where the slinky was shortest and to connect that to the experience of the body: they found that they ‘looked too much at the slinky to have time to think about the feeling’. In earlier work, with supervised visits, students would have been asked to ride once more [1].

Interestingly, in the discussion on relation between force and acceleration, the students connected the length of the slinky to how many G’s they were experiencing. This type of discussion revealed that they were familiar with using a spring to measure force, and could use Hooke’s law to relate the length to the force on the body, and express it in terms of a ‘g factor’.

5.3.3. A group of well-prepared 15 year olds.

The final group came from a school more than 300 km north of Gothenburg. They had had time to fill in a questionnaire with photo sequence in figure 2 during the bus ride, and were able to provide reflected responses during the interview. They were convinced that they would feel heavy at the bottom and light at the top, or just after. In the discussions, they used the words ‘force’ and

‘acceleration’ in a way none of the earlier groups of 15 year olds had done, but were more interested in the experience than the older students had been. After the ride, most of the students in this group were happy to express that their predictions agreed with observations. They also discussed how many G’s they experienced, relating to the length of the slinky during different parts of the ride. These discussions were similar to the discussions with the older students.

It is worth noting that responses by this group were much richer and more elaborate. After responding on paper, they had had time to reflect some more, and possibly to discuss with their peers. Whereas the first groups of 12–15 year olds focused on their own experience, with little connection to physics, and the group of older students wanted to do calculations, based on the screen shots, this final group of 15 year olds aimed to connect the embodied experience to a physical description in a conceptual and interesting way, while using a rich disciplinary language, using representations such as speech, gestures, graphs and mathematics.

This group of 15 year olds had been selected from several schools based on their interest in continued science studies. As part of the trip to Gothenburg, they also had other science activities, including visits to the university, and to the Onsala Space Observatory.

6. Discussion and conclusion

From the results presented above we can conclude that many students in all age groups had problems distinguishing between velocity and acceleration, often believing that velocity and acceleration are in the same direction. This reflects the most common situation in textbooks, where acceleration is typically introduced as uniformly accelerated motion starting from rest.

For the older students, a very common answer was that they need to calculate the answers (and directions) of the \mathbf{v} and \mathbf{a} vectors; This is also the traditional way to introduce acceleration in physics textbooks. Many earlier studies have, indeed, found that students often rely on mathematical representations, whereas their conceptual understanding may be limited. Many of the students rely on the importance of the mathematical representation for understanding, while at the same time not being and they are not aware of what to expect. The students will thus not be able to judge their answers, as they lack the link between mathematics and the real-life experience; they are used to judge situations based on the most compelling visual attributes [20], such as examples in text books, or what they see when *only observing* an experiment such as the family ride. However, after the embodied experience students were much more confident and reported that they now understood the situation and could explain it both conceptually and mathematically.

For the younger students, we saw the same pattern, although they did not reason from a mathematical perspective. Their discussions before the ride revealed many different expectations about what would happen and how it would feel. After the ride, many correctly reported where they felt heaviest and lightest and also made relevant connections to the semiotic resources (graphs, images, etc) that were presented for them before the ride. The results also indicate that many students are not used to interpret graphical representations, nor to relate motion to the experience of the body.

From the results, and to answer the research questions, we conclude that the embodied experience worked as an effective transductive link between the other semiotic resources that the students used in their meaning-making of the phenomenon involved in this activity. We also

found that the scaffolding experiences that were provided by the authors during discussions *before the ride* were crucial to enable students to discern the disciplinary-specific affordances of the semiotic resources involved in this activity: it is important to point out to the students what to look for (disciplinary discernment, [5]) from the semiotic resources used and what embodied sensations to ‘listen to’, and *how to connect them*, as found also in earlier research (see, for example, [14]).

Furthermore, our results indicates how useful unconventional semiotic resources can be. In this project we used a family ride in an amusement park together with a slinky. These resources, together with more conventional one’s, such as graphs and mathematics as well as sequences of screen shots, etc, allowed our participants to build a deeper understanding of the motion and forces involved.

In conclusion, we find that the family ride used in this paper offers opportunities to practice transfer from textbook representations to real-life situations and back, via the embodied experience. As a consequence, we suggest that teachers use playground or amusement parks to offer students embodied experiences as a transductive link between other semiotic resources used, to enhance students’ possibilities for meaning-making and learning physics.

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