# Smartphones as Experimental Tools: Different Methods to Determine the Gravitational Acceleration in Classroom Physics by Using Everyday Devices

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**Abstract**
New media technology becomes more and more important for our daily life as well as for teaching physics. Within the scope of our N.E.T. research project we develop experiments using **N**ew Media **E**xperimental **T**ools (N.E.T.) in physics education and study their influence on students learning abilities. We want to present the possibilities e.g. of smartphones as special new media devices serving as tools for conducting experiments in classroom physics and in daily life as well. In this paper, we give an overview about different methods for determining the gravitational acceleration as one of the most fundamental parameter in physics by using these easy-to-have and easy-to-use everyday tools. The theoretically backgrounds of the experiments range from the simple use of the law of gravitation to the coefficient of restitution and refer to different physical concepts (mechanics and acoustics). So each of these experiments requires different pre-conditions and it's possible to conduct these experiments and determine this most fundamental parameter in classroom physics by completely different types of learners (high-school as well as college level).
**Keywords**: Smartphone-Physics, experimental tools, Situated Learning, gravitational acceleration.

## Introduction

Mobile phones[1] and Smartphones have become more and more everyday tools – for us and especially for students as well. Besides the well-known negative effects of these devices, the increasing use and technical development of these tools could enrich physics lessons, too. Within the scope of our N.E.T. research project we develop experiments using **N**ew Media **E**xperimental **T**ools (N.E.T.) in physics education and study their influence on students learning abilities. The focus of the project is therefore using mobile phones in general and smartphones in particular as an experiment tool - a topic that has been somewhat neglected in the field of educational research to date. In this case different initial examples to different topics has been discussed yet (Falcão et al., 2009; Hammond & Assefa, 2007; Kuhn & Vogt, 2012a; 2012b; Kuhn et al., 2011; Schwarz, Vogt & Kuhn, 2012; Van Domelen, 2007; Villa, 2009; Vogt & Kuhn, 2012a; 2012b; Vogt et. al., 2011).

Especially smartphones are very suitable for serving as experimental tools, because they are usually equipped with a number of sensors. For example, most of the smartphones involve a microphone as well as acceleration and field strength sensors, a light intensity sensor and a GPS

[1] When referring to "mobile phones" in this context, we mean devices whose main function is to enable wireless and location-independent telephoning; in addition, they communicate with the telephone networks via wireless technology and integrate several simple software applications. "Smartphones", on the other hand, are mobile phones, which – alongside their function as wireless telephone - provide extensive additional computer functionality and connectivity in comparison to a traditional modern mobile phone and can be equipped with customized functions by the user by installing additional programs (so-called applications; short form: apps). As a result, a smartphone can be seen as a small transportable computer (PDA) with the additional functionality of a mobile phone.

receiver. As all the sensors can be read by appropriate software (apps), a large number of quantitative experiments in physics classroom can be conducted with smartphones.

This paper includes relevant examples of the project "N.E.T. – New Media Experimental Tools" concerning the gravitational acceleration. N.E.T. is located within the framework of situated learning theory. The project is based on the assumption that, alongside the authenticity of the topic, the authenticity of the media used in experiments has a positive learning impact in physics instruction, thus material-aided situated learning. Hence, this aspect aims to provide a theoretical extension or specification of situated learning (aspects to date: thematic, episodic, social (Kuhn et al., 2011). In concrete terms, this assumption means that the cognitive and motivational learning success of the learners with regard to experimentation in physics lessons is greater, if they explore a physical phenomenon with experimental tools (in particular with "(every day) new media") that they use every day, albeit possibly for different purposes. The focus of this aspect of research is, first, the development of physical experiments using authentic media of this kind. In a second phase, an empirical study will explore the impact of these media on learning and motivation in everyday physics lessons with a quasi-experimental control/test group research design.

In this paper, we want to present an overview about different methods for determining the gravitational acceleration as one of the most fundamental parameter in physics by using easy-to-have and easy-to-use everyday mobile phones or Smartphones.

## Exploring the Gravitational Acceleration with a Smartphone Acceleration Sensor

This part of the article focuses on providing suggestions how a smartphone can be used to improve mechanics lessons, in particular when used as an accelerometer in the context of laws governing free fall. As software, the app *SPARKvue* was used in the experiments described below together with an iPhone or an iPod touch (Android devices could use the *Accelogger* app)[2]. The values measured by the smartphone were then exported to a spreadsheet application for analysis (e.g. MS Excel) (see below).

### Mode of operation of acceleration sensors in smartphones

It makes sense to fundamentally understand how acceleration sensors work before using them in lessons. They are micro-systems that process mechanical and electrical information, so-called micro-electro-mechanical-systems (MEMS). In the simplest case, an acceleration sensor consists of a seismic mass that is mounted on spiral springs and can therefore move freely in one direction. If an acceleration $a$ takes effect in this direction, it causes the mass $m$ to move by the distance $x$. This change in position can be measured with piezoresistive, piezoelectric or capacitive methods and is a measurement of the current acceleration (Glück, 2005). In most cases, however, the measurement is made capacitive. Figure 1 shows a simplified design of a sensor of this kind: Three silicon sheets, which are disposed in parallel and connected to each other with spiral springs, make up a series connection of two capacitors. The two outer sheets are fixed; the middle sheet, which forms the seismic mass, is mobile. Acceleration causes the distance between the sheets to shift, leading to changes in capacity. These are measured and converted into an acceleration value. Strictly speaking, they are therefore not acceleration sensors, but force sensors.

[2] For a short, brief overview of the experiment setting including the description of the app: see Vogt & Kuhn, 2012a.

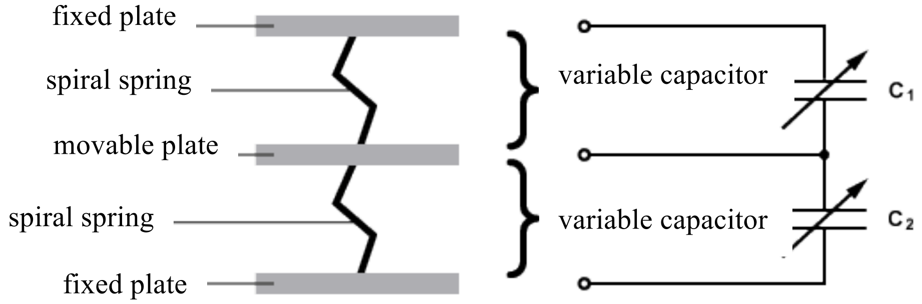


***Fig. 1.*** *Design and mode of operation of acceleration sensors (Vogt & Kuhn, 2012a; Schnabel, 2010).*

To measure acceleration three-dimensionally three sensors have to be included in a smartphone. These sensors have to be positioned orthogonally to each other and determine the acceleration parts $a_x$, $a_y$ and $a_z$ of each spatial direction ($x$-, $y$- and $z$-axis) independently (s. Figure 2).

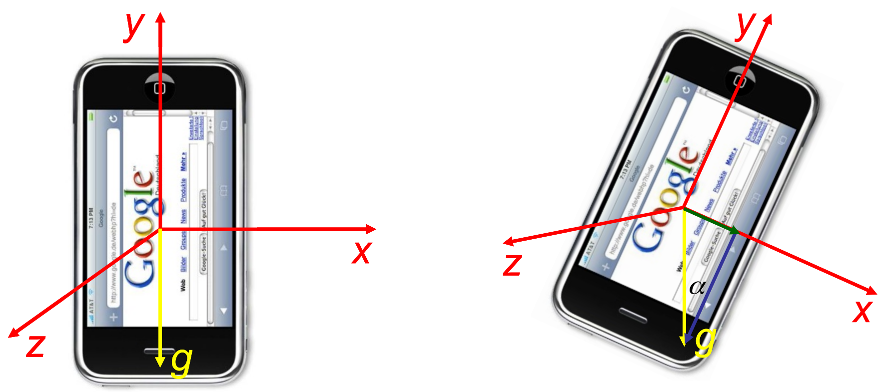


***Fig. 2****. The orientation of the three independent acceleration-sensors of an iPod touch; the sensors measure the acceleration in the direction of the three plotted axis (Vogt & Kuhn, 2012a)*

**Free fall in the physics laboratory or at home**

A suitable way of examining free fall is to suspend the smartphone from a piece of string, which is burnt through to start the fall (see Figure 3a). In order to avoid damaging the device, a soft object is placed under the cell telephone (e.g. a cushion) for it to land on. After having started the measurement of acceleration with a measuring frequency[3] of 100 Hz, the string is burnt through and the free fall commences. The acceleration value measured can be seen in Figure 3b.

[3] The measuring frequency has to be adjusted for the app if necessary.

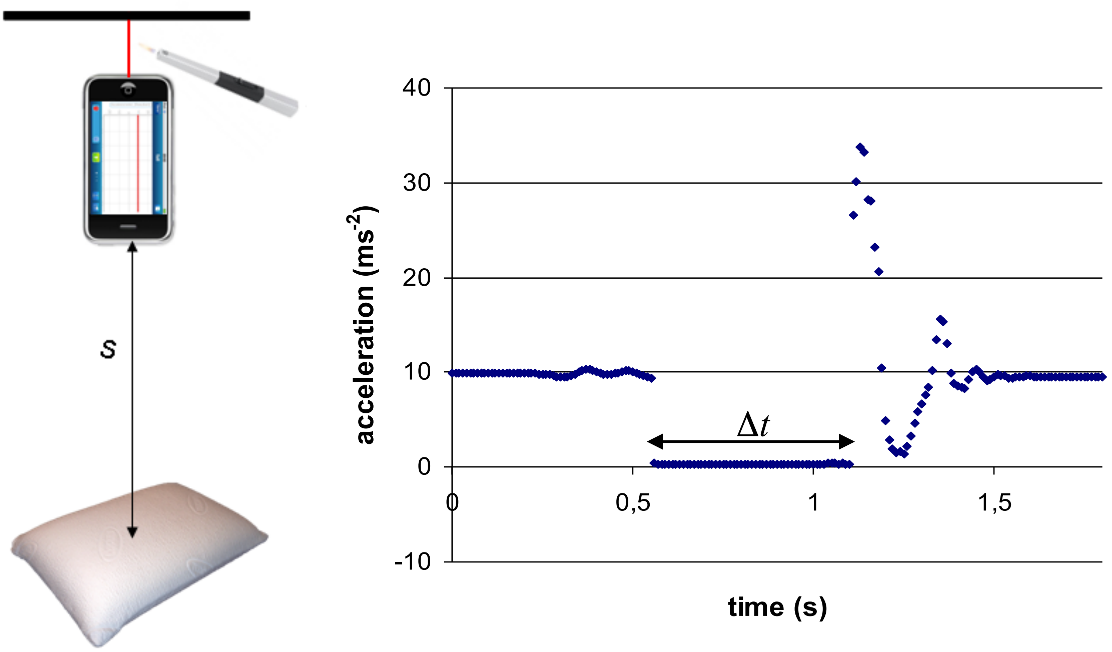


***Fig. 3.*** *Free fall at home: experimental set-up (a) and acceleration process (b); presentation of measurements after the export of data from the smartphone into MS Excel (Vogt & Kuhn, 2012a)*

At first, the smartphone is suspended from the string and the acceleration of gravity of 9.81 $ms^{-2}$ takes effect (Figure 3a). After approx. 0.6 s, the free fall begins and the sensors cannot register any acceleration, because they are being accelerated with 1 $g$ themselves.[4] This state is maintained until the cell phone's fall is stopped by landing on the soft object. As can be seen in Figure 3b, the sensor continues to move slightly and returns to complete immobility after a period of 1.5 s. The measurement can then be terminated and exported to a spreadsheet program (e.g. MS Excel) in order to determine the time it takes to fall $\Delta t$.

It is obvious that the smartphone has a dual function in this experiment; it serves both as falling body and as electronic gauge, making it possible to determine the free-fall time with a good degree of accuracy. For the measurement example described, the falling time was calculated to be $\Delta t$ = 0.56 s for a falling distance of $s$ = 1.575 m. If these values are applied to the distance-time equation for uniform acceleration (initial distance and initial speed equal zero and the smartphone is accelerated by the gravitational field);

$$s = \frac{1}{2} g t^2 \qquad (1)$$

the acceleration of gravity $g$ is calculated with the formula;

$$g = \frac{2s}{t^2} = (10{,}0 \pm 0{,}2) \frac{\text{m}}{\text{s}^2}, \qquad (2)$$

delivering a sufficient degree of accuracy for school instruction.

[4] This is difficult to understand for pupils, because they perceive the exact opposite: At first, the device suspends motionless from a string and then falls, accelerating to the floor. This is why they can only understand the measured acceleration process if they have previously been instructed on the way acceleration sensors function. In addition, the learners' previous experience of being pressed to the floor in a lift accelerating downwards, and the resulting conclusion that one is weightless in a free-falling lift, can also help them understand the process.

**Free fall in a recreation park**

It is particularly interesting to investigate the free fall of a free-fall tower, which can sometimes be found in recreation parks. Figure 4 shows the falling tower at Holiday Park (Hassloch/Rhineland-Palatinate, Germany), which lifts three four-seat gondolas to a height of 62 m. After a short break, the free fall commences and is braked after a fall of 36.3 m. The acceleration process measured by the smartphone is illustrated in Figure 5. Similar to the experiment of free fall over a short distance described above, the sensors first measure the acceleration of gravity, then during the fall record considerably lower values and a high level of acceleration for the braking procedure. The fact that the acceleration during the fall is not zero shows that the value of the acceleration of the fall is lower than gravitational acceleration and thus that the fall isn't completely free, but is braked by the free-fall tower operator. Nevertheless, the "free-fall time" can be extracted from the data set (it is approx. 2.6 s in the measurement example), whereby – applying formula (1) – the free-fall distance is estimated to be 33 m. This result differs from the operator's information by 3.6 m, i.e., an approx. 10% deviation, and is considered acceptable for a school experiment.

Alongside the free-fall tower, other rides in recreation parks can be analyzed in experiments with the help of acceleration sensors and provide learning opportunities for mechanics instruction.

In both experiments, the benefit of using acceleration sensors of this kind is evident: As neither a cable connecting the sensor and the computer nor a connection to a motion transformer is necessary, the accelerations can be measured without any disturbance. Another advantage of the smartphone as an experimental tool is that it is simple to use. Pupils are familiar with the device and the apps can be operated intuitively. Experts predict that conventional cell phones will have disappeared completely from the market in a few years. By then at the latest, the pupils will all possess an own "measurement data acquisition system", which is available for lessons at school or at home and - from our point-of-view - is a valuable resource, for which sensible applications should be developed and examined as soon as possible.


*Fig. 4. Free-fall tower in the Holiday Park (Hassloch/Rhineland-Palatinate, Germany)*

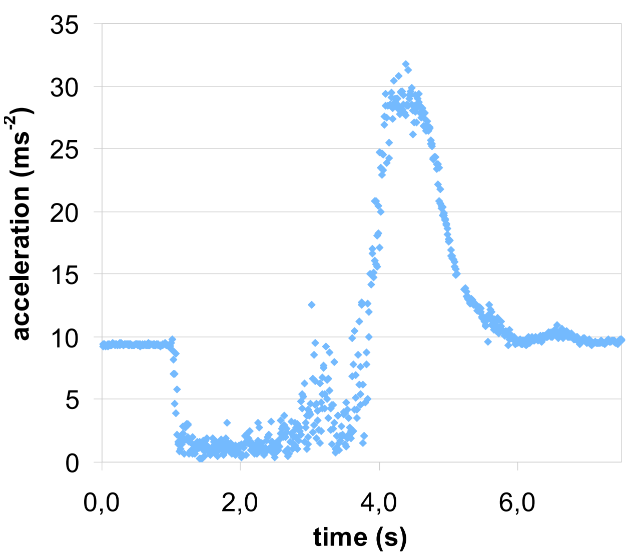


*Fig. 5. Acceleration process of the free-fall tower (presentation of measurements after the export of data from the smartphone into MS Excel)*

**Determination of Gravitational Acceleration by Using Bouncing Balls and Smartphones**

Further interesting experiments can be performed and fundamental physical relationships can be explored with so-called super balls or bouncy balls, e. g. the determination of gravity *g*. The basic idea behind this was described by Pape (2000) and Sprockhoff (1961): The initial and final heights and the complete duration of all the bounces are measured for a certain number of bounces by the ball. On the basis of this data, the acceleration of gravity can be approximately calculated, if air drag on the ball is neglected. However, in practice, it becomes clear that measuring the height of the last bounce in the process is problematic. The person performing the experiment either has to make a good estimation of its height or films the bounce in front of a measuring stick. The method is based on the important assumption that each of the individual bounces of the ball loses the same percentage of mechanical energy; the coefficient of restitution *k* therefore remains the same.[5]

### Acoustic data measurement

Inspired by the research referred to above, our objective was to find an effective way of collecting data about a super ball's bouncing process in order to measure the speed of gravity, free fall, the throw and the coefficients of restitutions in an experiment. We found the use of an acoustic measure particularly effective, as described in Aguiar and Laudares (2003), Schwarz and Vogt (2004) as well as in White et al. (2007). The sounds made by the impacts of the ball are recorded with a microphone as voltage signals over a certain period of time. This produces a chronological sequence for a super ball, with the sound made by the impacts resulting in surprisingly sharp peaks, as can be seen Figure 6. These peaks can be seen as time markers. The data was collected using an iPad equipped with the "Oscilloscope" app[6], which can also be installed on an iPhone or iPod touch[7]. The simple experiment set-up can be seen in Figure 7.

The person conducting the experiment should select the highest possible buffer size (2000 ms), start the measurement and then release the super ball onto a solid, hard, horizontal and smooth surface, e.g. a stone slab.

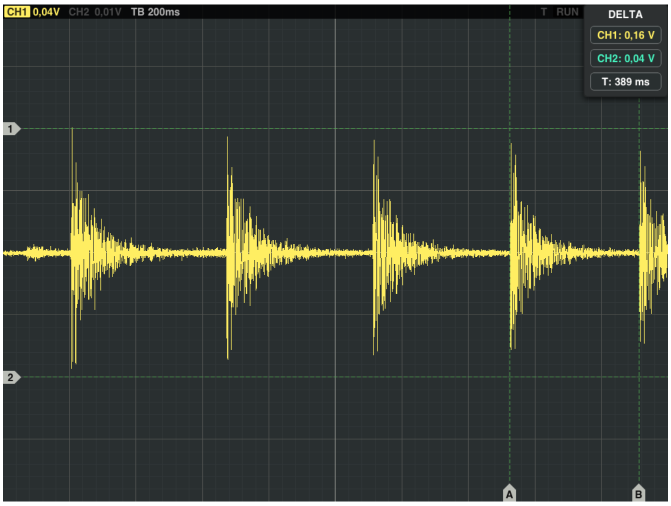


***Fig. 6.*** *Chronological sequence of the sound signals made by a bouncing ball (Schwarz, Vogt & Kuhn, 2012)*

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[5] For a short, brief overview of the experiment setting including the description of the app: see Schwarz, Vogt & Kuhn, 2012.

[6] The "Oscilloscope" app can be bought in the Apple Store at the following link for $19.99: http://itunes.apple.com/us/app/oscilloscope/id388636804 [temporary web-address]

[7] Alternatively, a commercial measuring system or a free sound editor (e.g. Audacity) can be used to make the acoustic recordings.

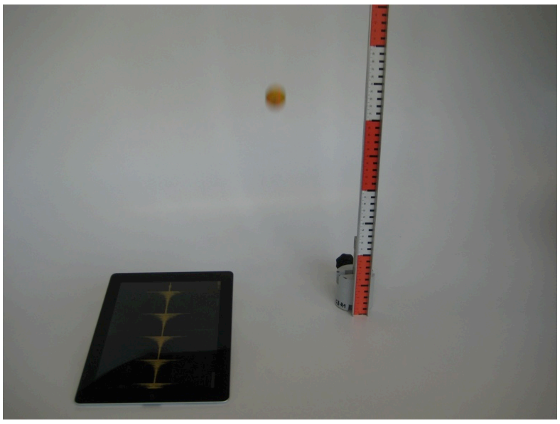

***Fig. 7.*** *Experiment set-up for the acoustic measurement using an iPad (Schwarz, Vogt & Kuhn, 2012)*

**The energy loss on impact**

A vertically thrown ball rebounds upwards between two impacts, which have an identical beginning and end height, i.e. $h = 0$ m. Therefore the rise and fall times $t_H$ of the ball are given with the following equation:

$$t_{\mathrm{H}} = \frac{v_0}{g} \quad (3)$$

We measure the time between two impacts, i.e. $\Delta t = 2t_{\mathrm{H}}$. The initial velocity $v_0$ is also the velocity with which the ball hits the floor again. The kinetic energies $E_{\mathrm{kin1}}$ and $E_{\mathrm{kin2}}$ between two subsequent impacts behave like the squares of the impact velocities. As a result, taking equation (3) and the coefficient of restitution $k = \frac{E_{kin2}}{E_{kin1}}$, we obtain:

$$k = \frac{E_{\mathrm{kin2}}}{E_{\mathrm{kin1}}} = \frac{v_{02}^2}{v_{01}^2} = \frac{h_2}{h_1} = \frac{t_{\mathrm{H2}}^2}{t_{\mathrm{H1}}^2} = \frac{\Delta t_2^2}{\Delta t_1^2}. \quad (4)$$

As can be seen in Table 1, the coefficient of restitution remains almost completely constant, even for very different heights (0.7 m and 0.3 m). We can therefore assume that it remains constant for the first three impacts with an initial height of 0.7 m. As it is only possible to measure and quantitatively analyse the last two seconds of the measurement with the app, it was not possible with an initial height of 0.7 m to record further impacts and, as a result, confirm the constancy $k$ with just one measurement.

| Initial height in m | Impact | *t* in s | Δ*t* in s | *k* |
|---|---|---|---|---|
| 0.7 | 1 | 0.248 | | |
| | 2 | 0.955 | 0.707 | |
| | 3 | 1.617 | 0.662 | 0.88 |
| 0.3 | 1 | 0.201 | | |
| | 2 | 0.670 | 0.469 | |
| | 3 | 1.109 | 0.439 | 0.88 |
| | 4 | 1.523 | 0.414 | 0.89 |
| | 5 | 1.912 | 0.389 | 0.88 |

***Table 1.*** *Calculation of the energy loss caused by the impact times for two different initial heights*

**Determination of the acceleration of gravity**

In order to determine *g,* the maximum height of the ball between two impacts has to be measured at least once during the bouncing process. It makes sense to select the initial height of the ball for this, which was 0.7 m for the experiment described below, as it is easily measured. The analysis was conducted as follows.

Assuming that the person performing the experiment has calculated the relative energy loss per impact *k* as described previously and has ascertained that the value remains constant from bounce to bounce, it is possible to determine the maximum height $h_2$ of the ball after its first impact with the floor. If $h_1$ designates the measured initial height, then the maximum height is given by:

$$h_2 = k \cdot h_1 \tag{5}$$

The free-fall time of the ball from its height $h_2$ until its impact is half of the time $\Delta t$ between two impacts (Figure 8). By taking this consideration, equation (5) and the distance-time law of free fall into account, *g* is obtained as follows:

$$g = \frac{2h_2}{(0{,}5 \cdot \Delta t)^2} = \frac{2kh_1}{(0{,}5 \cdot \Delta t)^2} \tag{6}$$

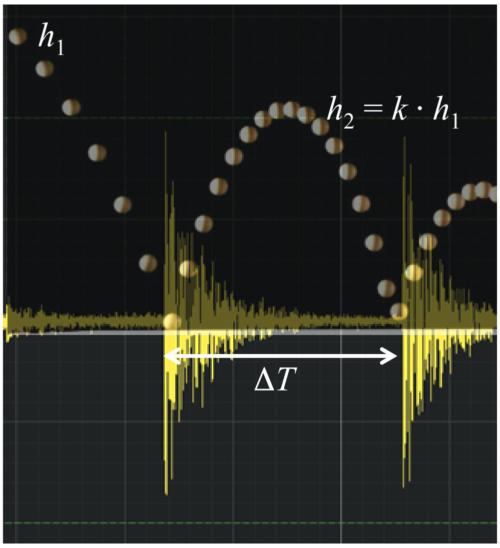


***Fig. 8.*** *Determination of the critical sizes (Schwarz, Vogt & Kuhn, 2012)*

| **Impact times** | **Calculated value of *g* (m/s²)** |
|---|---|
| $t_1$ = 0.248 s; $t_2$ = 0.955 s; $t_3$ = 1.617 s | 9.82 |
| $t_1$ = 0.201 s, $t_2$ = 0.898 s, $t_3$ = 1.549 s | 10.06 |
| $t_1$ = 0.129 s, $t_2$ = 0.830 s, $t_3$ = 1.479 s | 9.77 |

***Table 2.*** *Determination of gravitational acceleration on the basis of three impact times, with an initial height of 0.7 m each time (Schwarz, Vogt & Kuhn, 2012)*

The results of the three measurements with the same initial height can be seen in Table 2. In conclusion, it is possible to measure the acceleration of gravity *g* and the relative energy loss of an impact using a good super ball with a single sound recording of the sound produced by the impacts. The experiment yields a result that is sufficiently accurate for the purposes of physics instruction.

**Discussion**

Simple and obvious experiments as well as more complex experiments can be conducted with smartphones to determine fundamental physical variables. In this regard this paper presents different methods to determine the acceleration due to gravity as one of the most fundamental parameter in physics by using easy-to-have and easy-to-use everyday Smartphones. With this we go one step ahead in comparison to earlier papers (Falcão et al., 2009; Hammond & Assefa, 2007; Kuhn, Vogt & Müller, 2011; Van Domelen, 2007; Villa, 2009; Vogt, Kuhn & Müller, 2011) and present possibilities for quantitative studies of high quality with these everyday tools in physics classroom education.

The first method to determine the gravitational acceleration described in chapter 2 allows to determine the gravitational acceleration in a simple way: Using the acceleration sensor of smartphones students even at high school level could study this fundamental parameter by conducting the described free fall experiment in two ways – in the classroom or at home as well as in a recreation park. They only have to use one of the relevant apps to read out the acceleration data and record the data of the acceleration sensor during free fall. Using the distance-time equation for uniform acceleration the gravitational acceleration could be calculated by inserting the falling time $\Delta t$ (determine by the recorded acceleration data read out of the app; this would be the time, during which the acceleration data is equal to zero) and the falling height. Although this method is comparatively simple and could be used at different locations the examples in chapter 2 show that the accuracy of measurements is – concerning classroom conditions – absolutely satisfying.

The second method described in chapter 3 is much more demanding than the first one to determine the gravitational acceleration and focusses on students at least at college level: Using the microphone of smartphones and bouncing super-balls. After a super-ball is dropped it bounces different times and loses height. The important assumption is that each of the individual bounces of the ball loses the same percentage of mechanical energy and so the coefficient of restitution $k$ therefore remains the same. In this experiment the initial and final heights and the complete duration of all the bounces are acoustically measured with the smartphone and a relevant app (working as an acoustical storage oscilloscope) for a certain number of bounces by the ball. With this the restitution coefficient $k$ can be calculated and can be used with the distance-time law of free fall for determining the gravitational acceleration. Although this method is much more demanding than the free fall determination of the gravitational acceleration our measures can show that it isn't less accuracy and it's as simple to conduct as the free fall experiment.

**Conclusion and Outlook**

Alongside the well-known negative effects of mobile phones on everyday school life, modern mobile telephones – especially smartphones – can be used to enhance physics classroom education in many ways, especially in order to perform experiments when used as an experiment tool. With this paper, on the one hand, we want to present two different methods for determining the fundamental parameter $g$ which are both simple to conduct for students but of different grade and so focused on different types of learners. By the way, on the other hand, we want to link this conceptual development with the corresponding theoretical framework and the empirical research. For this it is necessary to investigate the impact of this material-aided situated learning approach on learning and motivation and to evaluate, which factor might make an used material of an experiment more successful than another, or in other words: to evaluate a degree of material-aided situatedness.

In this view, recent studies in this context show that it could be an important factor to which degree the students themselves perceive the learning material as authentic (in sense of relevant, useable) for their own daily life (Kuhn, 2010). So it needs – among other things – an instrument to assess perceived authenticity of the used material of the experiments by the learners (as manipulation check). For this an instrument to assess motivation with a subscale "Authenticity" was developed to evaluate such factor (figure 9).

| Item | value[8] | | | | | |
|---|---|---|---|---|---|---|
| Experiments, which we worked on in physics lessons, are helpful for everyday life. | ① | ② | ③ | ④ | ⑤ | ⑥ |
| The materials of the experiments, with which we work in physics lessons, are helpful for everyday life. | ① | ② | ③ | ④ | ⑤ | ⑥ |
| Experiments, which we worked on in physics lessons, are related to everyday life. | ① | ② | ③ | ④ | ⑤ | ⑥ |
| The materials of the experiments, with which we work in physics lessons, are related to everyday life. | ① | ② | ③ | ④ | ⑤ | ⑥ |
| Experiments in physics lessons are interesting for things, which we deal with outside school, too. | ① | ② | ③ | ④ | ⑤ | ⑥ |
| The materials of the experiments, with which we work in physics lessons, are useful for everyday life. | ① | ② | ③ | ④ | ⑤ | ⑥ |
| Materials of the experiments, in physics lessons are interesting for topics, with which I am concerned outside school, too. | ① | ② | ③ | ④ | ⑤ | ⑥ |
| Experiments, which we worked on in physics lessons, are useful for everyday life. | ① | ② | ③ | ④ | ⑤ | ⑥ |

***Fig. 9.*** *Items of the subscale "Authenticity" to measure perceived authenticity of the used material of the experiments by the learners*

We studied the reliability of this instrument with 411 students. The cronbachs α value (as reliability indicator was satisfactory) of the subscale "Authenticity" is cronbachs $\alpha = 0.92$; this value indicates a very high reliability of this subscale. So we developed a reliable instrument to evaluate the influence of the important factor "Authenticity" of students learning and motivation.

<table>
<tr><th>Week</th><th>Lesson</th><th>Experimental group</th><th>Control group</th></tr>
<tr><td rowspan="2">1</td><td>1</td><td colspan="2" rowspan="2">Pre-tests<br>Motivation test, performance test, experimental skills, general intelligence, reading skills</td></tr>
<tr><td>2</td></tr>
<tr><td rowspan="2">2</td><td>3</td><td rowspan="2">Instruction phase<br>Instruction materials (experimental tasks) on the topic of "vibrations and waves" with mobile telephones as experiment tool</td><td rowspan="2">Instruction phase<br>Instruction materials (experimental tasks) on the topic of "vibrations and waves" with conventional experiment tools supplied by a manufacturer of teaching materials</td></tr>
<tr><td>4</td></tr>
<tr><td rowspan="2">3</td><td>5</td><td colspan="2" rowspan="2">- Determination of the speed of sound<br>- Types of sound wave (tone, sound, noise, impulse)<br>- Acoustic beat<br>- Sound propagation</td></tr>
<tr><td>6</td></tr>
<tr><td rowspan="2">4</td><td>7</td><td colspan="2" rowspan="2">Post-test<br>Motivation test, performance test, experimental skills, general intelligence, reading skills</td></tr>
<tr><td>8</td></tr>
<tr><td>5…8</td><td></td><td colspan="2">Conventional physics instruction</td></tr>
<tr><td rowspan="2">9</td><td>9</td><td colspan="2" rowspan="2">Follow-up test<br>Motivation test, performance test, experimental skills, general intelligence, reading skills</td></tr>
<tr><td>10</td></tr>
</table>

***Fig. 10.*** *Experimental design for a quasi-experimental test/control group survey "Learning outcomes of material-aided situated learning"*

[8] ①: Statement is wholeheartedly appropriate; ②: Statement is appropriate; ③: Statement is rather appropriate; ④: Statement is rather not appropriate; ⑤: Statement is not appropriate; ⑥: Statement is totally not appropriate.

With this we want to classify the degree of perceived authenticity of the used material of the experiments by the learners and use this for recommendations for material selection to teachers in the next step.

To investigate the impact of this approach on learning and motivation a quasi-experimental pilot study with a comparison of test and control groups is currently being performed on the topic of “vibrations and waves” in everyday physics classes. Approximately 100 pupils in four German “Realschule” (middle school) forms are participating in the study; both the test and control classes are taught by the same teachers (research design: figure 10). The learning contents and the instruction materials are completely identical in all of the groups; the only difference is the materials used for the experiments. For example, while acoustic beats are investigated in the control group with acoustic generators and a microphone supplied by a manufacturer of teaching materials, the pupils in the test group explore the same phenomenon with a smartphone. Initial findings of this study will be presented in spring 2013.

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