Results of a Design-Based-Research Study to Improve Students' Understanding of Simple Electric Circuits

Jan-Philipp Burde and Thomas Wilhelm

Abstract Most secondary school students fail to develop an adequate understanding of electric circuits as they tend to reason exclusively with current and resistance. Effective reasoning about electric circuits, however, requires a solid understanding of the concept of voltage. Against this background, a new teaching concept based on the electron gas model was developed with the goal to give students a qualitative but robust conception of voltage as a potential difference that causes the electric current. Using an air pressure analogy, the teaching concept aims to provide students with intuitive explanations that have their origins in the students' everyday experiences, e.g. with bicycle tires or air mattresses. Similarly to these everyday objects, where air pressure differences cause an airflow, voltage is introduced as an electric pressure difference across a resistor that causes the electric current. An empirical evaluation with 790 secondary school students shows that the new teaching concept leads to a significantly better conceptual understanding than traditional teaching approaches in Germany. Furthermore, 12 of the 14 participating teachers state that they plan to teach according to the new concept in future as they consider it to be a significant improvement.

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1 Motivation

Having taught the topic of simple electric circuits, most teachers will find that despite all their efforts, many students fail to develop an adequate understanding of voltage and electric circuits in general. Not realising the important role of voltage, students tend to reason exclusively with current and resistance when dealing with electric circuits (Cohen et al. 1983). As a result, they often have a series of alternative conceptions about electric circuits and generally struggle to understand how circuits work (Duit et al. 1985; Wilhelm and Hopf 2018). In particular, students often think of voltage as a property or a component of the electric current rather than an independent physical quantity that refers to a difference in electric potential (Rhöneck 1986). As students struggle to distinguish between the electric current and voltage, the former often dominates their understanding of electric circuits. As a consequence, these students see no need to conceptualise voltage as an independent physical quantity and hence fail to realise the important relation of cause and effect between voltage and current.

1.1 Background

Although the reasons for these learning difficulties are complex and numerous, three main problems can be identified based on prior research in science education: Firstly, for historical but not educational reasons, the concept of the electric current dominates teaching at the expense of potential and potential difference. For that reason, Cohen, Eylon & Ganiel point out that "*we need a curriculum that introduces the concept of potential difference first and* […] *clearly spells out the relation of cause and effect between pd* [potential difference] *and current*" (Cohen et al. 1983). Secondly, alternative explanations of voltage (e.g. $V = \Delta E/q$) make it difficult for the students to understand the mutual relationship of V, I and R in electric circuits as well as the fact that voltage represents a potential difference (Härtel 2012; Herrmann and Schmälzle 1984). Thirdly, an extensive but purely quantitative study of the formula $V = R \cdot I$ in physics lessons is highly problematic as "[…] *premature mathematization and 'exact' definitions* [often distort] *a conceptual understanding without really being able to replace it*" (Muckenfuß and Walz 1997, translation by the authors). In particular, the focus on the formula $V = R \cdot I$ can even strengthen the students' misconception that voltage must be a property of the electric current since the formula suggests that both physical quantities can only occur simultaneously (Muckenfuß and Walz 1997).

A more general problem lies in the fact that the physical processes in electric circuits are quite abstract and hard to imagine for students, because the electron movement, for example, is beyond direct perception. A way to help students understand the abstract concepts of electricity is to use models of electric circuits. While good models and analogies can indeed foster a deeper conceptual understanding, physics education research has shown that—contrary to popular belief—the use of the

widespread water circuit analogy using closed water pipes can reinforce typical alternative conceptions (Schwedes et al. 1995; Schwedes and Schilling 1983). Although the analogy is undoubtedly quite powerful from a purely physical point of view, the problem with it lies in the fact that students have no experience with closed water circuits from their everyday lives. In particular, they have no experience with water pressure in water pipes and think of water as an incompressible fluid. Since water under high pressure differs neither visibly nor palpably from water under low pressure, the water circuit analogy has proven less compelling to learners than generally expected (Burde and Wilhelm 2016). In contrast, the introduction of voltage as a potential difference has proven to be comparatively effective in promoting learning in a number of studies (Waltner et al. 2009; Gleixner 1998; Schumacher and Wiesner 1997). Examples of models of electric circuits that introduce voltage as a potential difference include the "rod model" developed in Munich by Gleixner (Gleixner 1998) and air pressure analogy used in the CASTLE curriculum by Steinberg and Wainwright (Steinberg and Wainwright 1993). While the former is suitable for illustrating potential differences, the latter has proven to be particularly promising to explain the relationship between potential difference and current as the electric potential is compared to air pressure. The advantage of the air pressure analogy over the water pressure analogy is that it has proven to be a highly intuitive and yet powerful analogy as students have a variety of experiences with air pressure from their everyday lives, e.g. with air mattresses, footballs or bicycle tyres (Burde and Wilhelm 2016).

1.2   Shortcomings of the CASTLE Curriculum

Although the CASTLE curriculum with its underlying air pressure analogy undoubtedly represents a promising approach to teaching electric circuits, there are several shortcomings regarding its design and evaluation. For example, in contradiction to the considerations made above, the CASTLE curriculum introduces the electric current before potential differences. As outlined before, this traditional content structure may in fact prevent students from understanding the important role that potential differences play in electric circuits as too much emphasis is placed on the electric current and too little emphasis is placed on the cause-effect-relationship between voltage and current. In this context, Cohen, Eylon & Ganiel point out that "*first impressions are strong and may impede a later, more rigorous, study of electricity*" (Cohen et al. 1983). Another drawback of the CASTLE curriculum lies in the fact that it primarily consists of a series of hands-on experiments with specially designed capacitors. In regard to the German school system, this does not only represent a problem as such capacitors can usually not be found in sufficient numbers in German physics classes, but also because the traditional lesson time of 45 min is generally ill-suited for a teaching concept that primarily relies on hands-on experiments. Another point of criticism is that the learning effectiveness of the CASTLE curriculum has never been empirically evaluated. Although its authors claim that it leads to significantly larger

achievement gains than traditional approaches to teaching electric circuits (Steinberg and Wainwright 1993), no empirical results of a study on its learning effectiveness have been published yet.

1.3 Goals and Research Questions

What has been lacking to date is a teaching concept that is based on the powerful air pressure analogy, but which introduces the concept of potential difference before the electric current and which is compatible with German school standards. What has also been lacking to date is an empirical evaluation of the learning effectiveness of such a teaching concept. In this paper, we will therefore first focus on the key ideas of the new teaching concept before presenting the results of its empirical evaluation. Here, we will particularly focus on the question whether the new teaching concept leads to a better conceptual understanding than traditional approaches to teaching electric circuits and whether the participating teachers consider the new teaching concept to be an improvement of their teaching practice.

2 The New Teaching Concept

Since the 1970s, a lot of research has been conducted on students' learning and students' alternative conceptions in introductory electricity (Duit et al. 1985; Wilhelm and Hopf 2018). However, the insights gained by numerous studies on domain-specific learning rarely had an adequate impact on teaching practice. From our perspective, this can at least partly be explained by the fact that knowing about students' alternative conceptions itself is not enough for teachers to successfully promote conceptual change in the classroom. In order to overcome typical alternative conceptions and successfully trigger conceptual change, educators need well-devised teaching resources that incorporate relevant research findings from the physics education community. While research results on students' alternative conceptions are specifically taken into account, diSessa's perspective on learning as the construction and reorganisation of previously only loosely connected elements of knowledge, called "p-prims", into a coherent mental structure forms the theoretical foundation of the teaching concept (Burde and Wilhelm 2018). These p-prims ("phenomenological primitives") represent a fragmentary and naive understanding of the physical world. They are primitive in the sense that they only constitute minimal abstractions from everyday experience (diSessa 1993). As diSessa points out, successful conceptual change can only occur if the students' prior knowledge in the form of p-prims is taken into account: "Students have a richness of conceptual resources to draw on. Attend to their ideas and help them build on the best of them" (diSessa 2008). A comprehensive description of diSessa's perspective on learning can be found in diSessa (2008).

In accordance with diSessa's perspective on learning, the new teaching concept aims to foster conceptual change by building on students' everyday physical intuitions, in this case with air pressure. In contrast to traditional approaches to teaching electric circuits, the new teaching concept does not focus on quantitative aspects, but on a qualitative understanding of voltage, current and resistance as well as their mutual relationship by constantly providing students with intuitive explanations that have their origins in the students' everyday experiences. Since the electric current generally seems to dominate students' understanding of electric circuits, a main objective of the new teaching concept is to establish potential differences as the starting point of any analysis of electric circuits. In accordance with the considerations of Cohen, Eylon & Ganiel, the objective is to make voltage and not the electric current the students' primary concept when thinking of circuits (Cohen et al. 1983).

2.1 Air Pressure Differences Cause an Airflow

In order to achieve this objective, the teaching concept builds on the students' intuitive concept of air pressure in the sense that "compressed air is under pressure, pushes against the walls and tries to expand". At the example of everyday objects such as bicycle tyres and air mattresses, students learn that air always flows from areas of high pressure to areas of low pressure. The conclusion then is that pressure differences are the cause for an airflow and that a conceptual distinction must be made between pressure and pressure difference. The explicit discussion of air pressure phenomena takes place against the background that learners often have conceptual difficulties in distinguishing between pressure and pressure difference. Towards the end of the unit on air pressure, a first concept of resistance is introduced, with students taking a piece of fabric (e.g. a scarf, collar or sleeve) and blowing air through it. By doing so, they learn that the thicker the piece of fabric is folded, the stronger the inhibition or obstruction of the airflow is (see Fig. 1). The inhibition or obstruction of the airflow by the fabric is then referred to as "resistance".
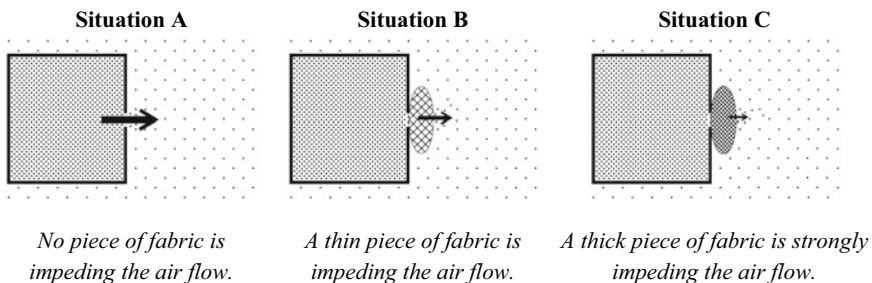

Situation A	Situation B	Situation C
No piece of fabric is impeding the air flow.	*A thin piece of fabric is impeding the air flow.*	*A thick piece of fabric is strongly impeding the air flow.*

Fig. 1 Pressure differences cause an airflow with a piece of fabric impeding the airflow

2.2 Battery, Electric Potential and Voltage

In the next unit, the idea of air pressure is transferred to the electric circuit by assuming that electrons, as particles, can move freely in a conductor, where they form an "electron gas". Since the electrons are negatively charged, they are pushed apart as far as possible by repulsion, which is why they uniformly fill the space available to them in the entire conductor. Due to the mutual Coulomb repulsion of the electrons, an electric pressure dependent on the electron density results. By assuming a surplus of electrons at the negative terminal of a battery and a shortage of electrons at its positive terminal, it is then argued that there is a high electric pressure at the negative terminal and the wire connected to it and a low electric pressure at the positive terminal and the wire connected to it.

In order to visually emphasise the similarity between air pressure and electric pressure, the dot-density representation already known from the air pressure examples is initially also used for open electric circuits (see Fig. 2, left). From this point on, however, it is better to use colour coding to visualise the electric pressure instead of the dot-density representation, since colour coding the electric pressure using coloured pencils has proven to be a more practical and timely method (see Fig. 2, right). In addition, colour coding also avoids the impression that the resistor consumes the moving electrons. In contrast to the often rather unsystematic choice of colours in existing teaching concepts, the colour scheme used in the concept presented in this paper is based on a convention that students should be familiar with from their everyday lives. Similarly to temperatures that are usually represented by the two colours red (high temperatures) and blue (low temperatures), e.g. in weather reports, thermal imaging cameras and water taps, a high electric pressure is represented by red, whereas a low electric pressure is represented by blue in this teaching concept. Since no absolute values are specified for the electric pressure, electrical grounding is deliberately not covered in the teaching concept.
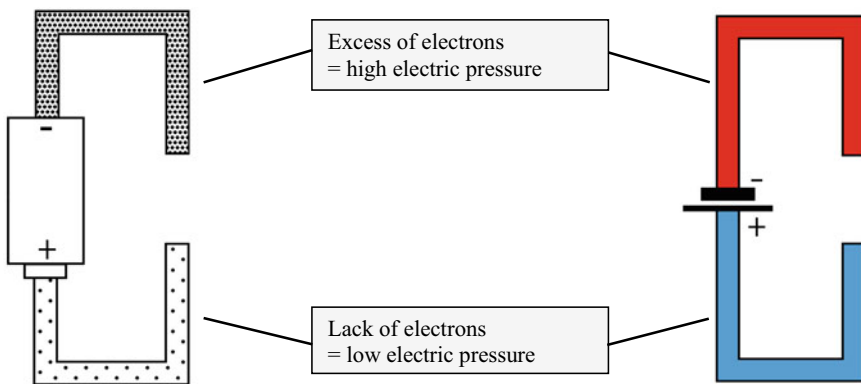

**Fig. 2** Dot-density representation (left) and colour coding (right) of the electric pressure

2.3 Electric Current and Resistance

In analogy to the air pressure examples discussed before, electric pressure differences are introduced as the cause of the electric current. For this purpose, a simple circuit consisting of a battery and a light bulb is used to discuss that the bulb will light up because the electric pressure difference across it will cause an electric current through the light bulb (see Fig. 3).

Based on the concept of resistance acquired in the unit on air pressure, the students are then given a qualitative idea of resistance in electric circuits and how it affects the electric current. Here, students learn that a resistor impedes the electric current in the same way as a piece of fabric impedes an airflow. The influence of voltage on electric current as well as of electrical resistance on electric current is described semi-quantitatively. The aim is to achieve a qualitative understanding of the causal relationships in the circuit, with the voltage causing the electric current and electrical resistance merely affecting it (see Fig. 4).

The previously purely qualitative concept of electrical resistance is then expanded to include a microscopic model of resistance. The aim here is to give students a better understanding of various conduction processes based on the Drude model. Ideal conductors, for example, are explained by the fact that the atomic cores in such a material are arranged very uniformly and the electrons hence almost never collide with the atomic cores (see Fig. 5, left). The fact that resistors have a not negligible electrical resistance can be explained in the model, for example, by assuming that the atomic cores are not uniformly arranged in the material, which means that collisions between the moving electrons and the atomic cores will frequently occur (see Fig. 5, right).

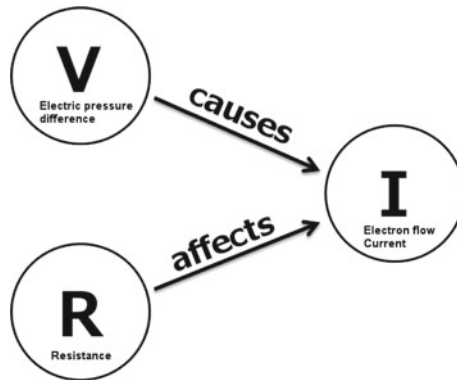**Fig. 3** Simple electric circuit with a light bulb
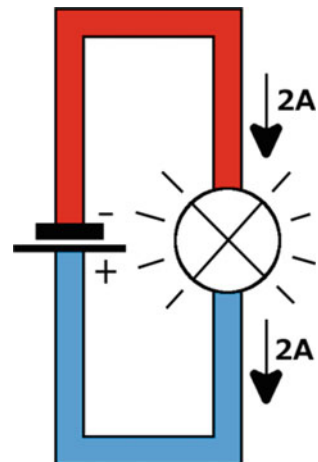
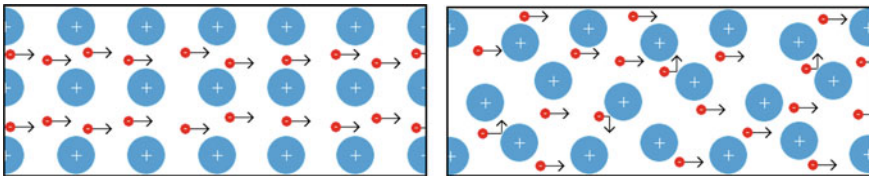**Fig. 4** Qualitative relationship of *V*, *I* and *R* in electric circuits

Fig. 5 Microscopic model of an ideal conductor (left) and a resistor (right)

2.4 Parallel Circuits

At the example of parallel circuits, students not only learn to clearly distinguish between the electric pressure concept and the electric current, but also that an (ideal) battery is a source of constant voltage and not constant current. In order to work out the electric current flowing through the different branches of a parallel circuit, students simply need to look at the electric pressure differences at the light bulbs and their electrical resistance. Based on the assumption that a big electric pressure difference causes an electric current of 2 A through a light bulb with a small electrical resistance and an electric current of 1 A through a light bulb with a big electrical resistance, students then simply need to add up the current through the different branches to get the current that needs to be supplied by the battery (see Fig. 6). By looking at electric pressure differences across the light bulbs first and then working out the electric current resulting from these pressure differences, this approach helps to make voltage—and not the electric current—the students' primary concept when analysing electric circuits. The colour coding also helps students to determine which light bulbs are connected in parallel as they simply need to compare the colours: If two bulbs have the same adjacent colours, they are connected in parallel (Fig. 6).

Fig. 6 Parallel circuit with three light bulbs. The right bulb has a higher electrical resistance than the other two
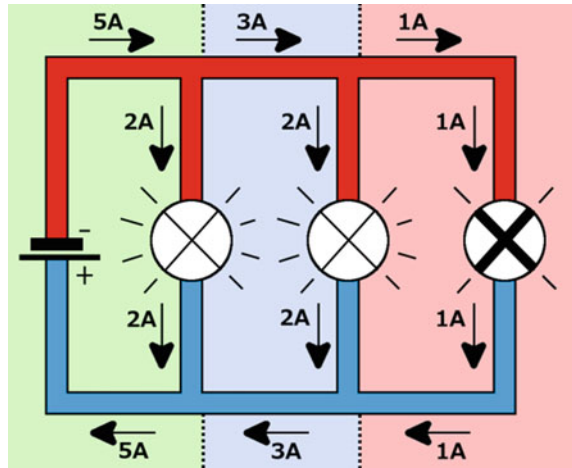

2.5 Capacitors

The analysis of capacitor charging and discharging using the model of "electric pressure" is supposed to help students understand the concept of transient states and dynamic model thinking, which they need for the analysis of series circuits. Transient states are introduced as it takes some time for the electric pressure in the different parts of the circuit to reach a steady state. In other words, the steady state is only achieved gradually over so-called transient states. By looking at the charging of a capacitor, the idea behind transient states becomes clearer.

In the very first moment, when the electric circuit gets connected to the battery, the battery causes a high electric pressure in section A and a low electric pressure in section C. In sections B and D, however, we still have a normal electric pressure since no electrons have flown through the light bulbs just yet (Fig. 7). During this transient state, electrons flow from section A through the top light bulb into section B, thereby increasing the electric pressure in section B. At the same time, we have electrons flowing from section D into section C, thereby decreasing the electric pressure in section D. As time goes by, the electric pressure in section B will increase until it aligns with the high electric pressure in section A and the electric pressure in section D will decrease until it aligns with the low electric pressure in section C. At that point, the steady state has been reached as the electric pressure in section B and D will not change anymore. The analysis described here also helps students overcome a number of common alternative conceptions, such as the belief that there are initially no electrons in the wires that electrons are stored inside the battery as oil is stored in an oil barrel or that the electric current flows sequentially from the negative terminal to the positive terminal.

Fig. 7 Transient state during
capacitor charging
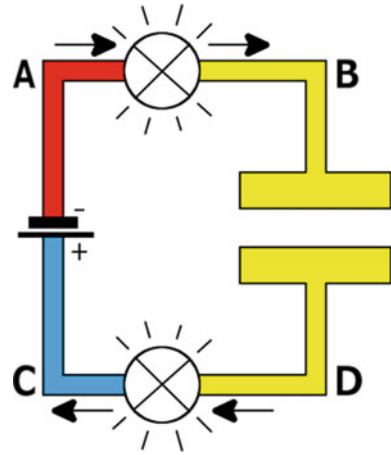
2.6 Series Circuits

As a next step, the concept of transient states is applied to a series circuit with a light
bulb with a high electrical resistance and a light bulb with a low electrical resistance
(see Fig. 8). At the beginning, when the electric circuit has not been connected to the
battery yet (initial state), we have a normal electric pressure in all parts of the circuit
(yellow). Once the battery is connected to the circuit (transient state), it creates a
high electric pressure in the top wire (red) and low electric pressure in the bottom
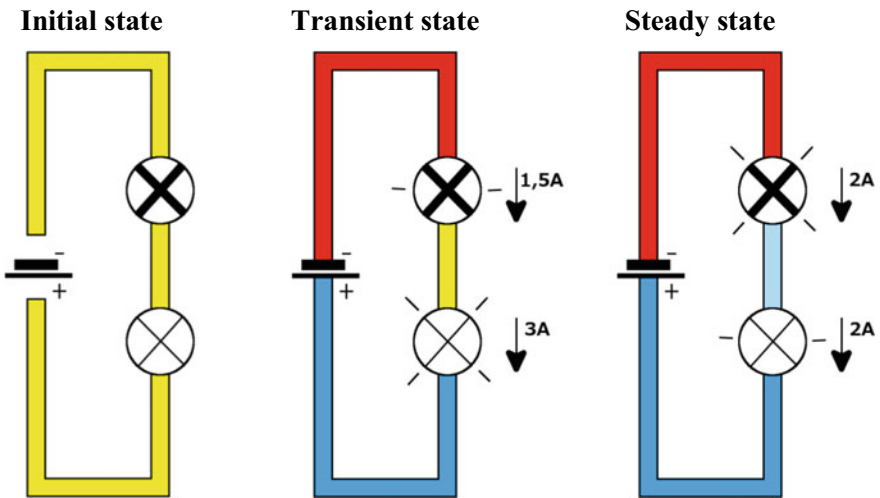wire (blue). Since no electrons have flown through the light bulbs at that point, the
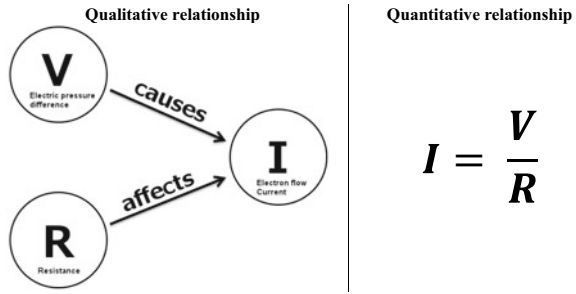

Fig. 8 Step by step analysis of a series circuit with two different light bulbs

Fig. 9 Transition from a
qualitative to a quantitative
relationship of *V*, *R* and *I*

$$I = \frac{V}{R}$$

electric pressure in the middle part of the wire remains unchanged (yellow). In that
transient state, we have the same electric pressure difference (= voltage) across both
light bulbs. However, since the top light bulb has a higher resistance than the bottom
light bulb, fewer electrons flow into the middle wire than out of it. Consequently, the
electric pressure in the middle part of the wire decreases. As the pressure decreases,
the electric pressure difference across the top light bulb increases, while the electric
pressure difference across the bottom light bulb decreases, with the effect that the
electric current through the top and bottom light bulb will align over time. Once the
electric current through the top and the bottom light bulb are identical, the electric
pressure in the middle part of the wire will not change anymore and the steady state
has been reached.

2.7 Quantitative Relationship

Once a qualitative understanding of "voltage", "current" and "resistance" and their
mutual relationship in simple electric circuits is established, the teaching concept
aims to transform this qualitative understanding into an understanding for the quan-
titative relationship $I = \frac{V}{R}$ (Fig. 9). A more detailed description of the teaching
concept and its theoretical background can be found in Burde (2018).

3 Quantitative Evaluation

3.1 Method and Sample

The purpose of the quantitative evaluation of the new curriculum was to find out
whether it leads to a higher learning gain than traditional approaches to teaching
electric circuits. In order to answer that question, a quasi-experimental field study
was conducted with $N = 790$ students from Frankfurt/Main, Germany, taking part
in the evaluation. The field study followed a pretest-posttest-control-group design,

where the control group (CG) was taught the traditional way by 11 teachers for an average of 23.5 lessons (SD = 11.9) and the slightly larger experimental group (EG) was taught according to the new curriculum by 14 teachers for an average of 24.3 lessons (SD = 9.8). The CG consisted of 17 junior high school classes with a total of $N = 357$ students and the EG consisted of 19 junior high school classes with a total of $N = 433$ students. Regarding the group size and the number of lessons taught, both groups were, thus, comparable. Furthermore, the topic of electric circuits was covered in both groups for the first time.

3.2 Test Instrument

In order to evaluate the students' conceptual understanding of electric circuits, the same valid and reliable two-tier multiple-choice test was used in both groups for the pre- and posttest. This test instrument was developed in Vienna by an independent research group without reference to the new teaching concept and contained 22 items in its original form (Urban-Woldron and Hopf 2012). Since the original test instrument with its 22 items primarily focused on the concepts of current and resistance, but not on voltage, we extended the original test by another four items that evaluated the students' conceptual understanding of voltage. Against the background that the new teaching concept primarily aims to give students a better conceptual understanding of voltage while only four out of 26 items of the test instrument focus on voltage, it can be assumed that the test instrument is unbiased towards the new teaching concept.

The two-tier structure of the diagnostic multiple-choice test provides deeper insight into students' reasoning about circuits as they do not only have to answer questions (first tier), but also give an explanation to their answer (second tier). By analysing the combination of answer and explanation, it is not only possible to identify false-positive answers (i.e. correct answers with an inadequate explanation), but also typical alternative conceptions about electric circuits. An item was only counted as correct if the answer (first tier) as well as the explanation (second tier) was given correctly. Since there were 26 items in total, the highest achievable score in the multiple-choice test is therefore 26 points.

3.3 Empirical Results

As the students were not taught independently of each other but were grouped in different classes, their learning success depends heavily upon their class membership. In the terminology of multi-level analyses (MLA), the students are "nested" in school classes. In order to appropriately account for this hierarchical data structure of the sample, a multi-level analysis was conducted. Such a multi-level analysis, also called hierarchical linear model (HLM), provides the most adequate estimate of the net effect of the treatment and its statistical uncertainty (Fig. 10).
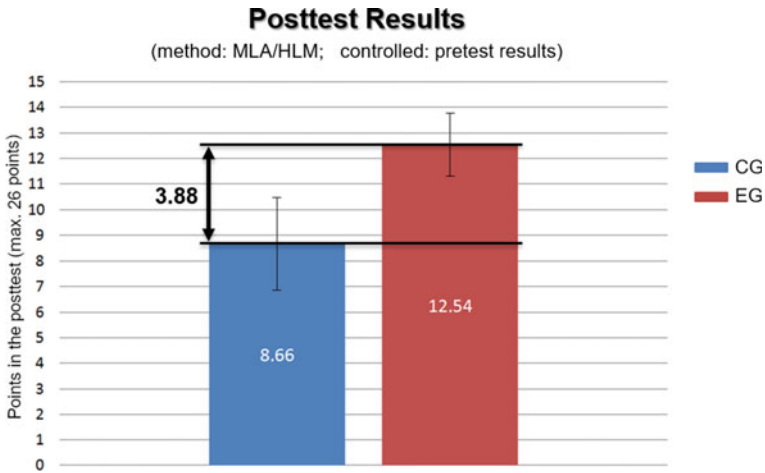
Fig. 10 Posttest results of the CG and EG

According to the HLM, the net effect of instruction is 3.88 points, which is a highly significant result and corresponds to a large effect of $d = .94$. It can, therefore, be assumed that the new teaching concept leads to a higher learning gain than traditional approaches to teaching electric circuits. Given the fact that the teachers of the experimental group taught their classes according to the new teaching concept for the first time and did not receive any in-service training, this is a remarkable result.

Thanks to the two-tier structure of the test instrument, it was also possible to analyse the students' alternative conceptions after instruction by means of a binary logistic multi-level analysis. In general, the new curriculum seems to lead to a better conceptual understanding as students of the EG either have a comparable, or significantly lower, probability to hold typical alternative conceptions after instruction than traditionally taught students. The new curriculum particularly appears to lead to a better understanding that voltage, in contrast to current, can only be measured between two points in a circuit because voltage refers to a difference in electric potential. A more detailed analysis of the empirical evaluation of the teaching concept can be found in Burde (2018).

4 Qualitative Evaluation

4.1 Method and Sample

Since the study was designed as a Design-Based-Research (DBR) project, it is not only of interest whether students achieve higher learning gains as a result of the new teaching concept, but also what the teachers think of it based on their practical

experience. In order to get an idea of the teachers' perspective on the teaching concept, an online questionnaire was created and distributed to the 14 participating teachers by e-mail. The questionnaire had a length of about 30 min and was divided into different sections. The primary goal was to find out where the teachers see the strengths and the weaknesses of the teaching concept and whether they plan to teach according to it again in future.

4.2 The Teachers' Perspective

All teachers considered the introduction of voltage as potential difference to be a good idea and said that the air pressure analogy in combination with colour coding leads to a better conceptual understanding of electric circuits. In particular, the teachers said that the relationship between voltage and current becomes clearer thanks to the new teaching concept. They also praised the concept for its good teaching resources and the fact that the students get a first microscopic model of the processes in electric circuits. It has been criticised, however, that the choice of colours in the colour coding scheme contradicts the convention commonly used in physics, according to which the positive terminal is usually coloured red and the negative terminal blue. Another point of criticism was that particularly younger students struggled with the concept of transient states to explain series circuits.

Overall, however, the teachers perceived the teaching concept presented in this paper as a significant improvement, which is why 12 of the 14 participating teachers state that they plan to teach according to it in future. From the perspective of design-researchers, this is a very positive result, since the acceptance of the teaching concept by practitioners is a necessary precondition for a broad adoption in schools. For a comprehensive description of the teachers' perspective, please refer to Burde (2018).

5   Outlook: The EPo-EKo Project

Based on the research findings of the project presented in this paper, the joint Design-Based Research project EPo-EKo ["Electricity with Potential and Electricity with Contexts" (spelled with a "K" in German)] is currently being carried out by three German and two Austrian universities. Among other goals, the project aims to find out whether the significantly better conceptual understanding of students instructed according to the new teaching concept can be replicated with a bigger sample of teachers and students. Furthermore, it is planned to investigate the effects of context-based materials on the students' interest, self-concept and conceptual understanding when teaching electric circuits. Additionally, the project aims to shed a light on the teachers' pedagogical content knowledge (PCK) and beliefs about teaching and learning introductory electricity and how they change due to the implementation of

new teaching materials. A more detailed description of the EPo-EKo project can be found in Haagen-Schützenhöfer, Burde, Hopf, Spatz & Wilhelm (2019).

References

Burde J-P (2018) Konzeption und Evaluation eines Unterrichtskonzepts zu einfachen Stromkreisen auf Basis des Elektronengasmodells. Logos, Berlin

Burde J-P, Wilhelm T (2016) Moment mal… (22) PdN-PidS 65(1):46–49

Burde J-P, Wilhelm T (2018) PERC proceedings 2017

Cohen R, Eylon B, Ganiel U (1983) Am J Phys 51(5):407–412

diSessa AA (1993) Cogn Instr 10(2–3):105–225

diSessa AA (2008) In: Vosniadou S (eds) International handbook of research on conceptual change. Routledge, London, pp 35–60

Duit R, Jung W, Rhöneck C (eds) (1985) Aspects of understanding electricity—proceedings of an international workshop (Schmidt & Klaunig, Kiel)

Gleixner C (1998) Einleuchtende Elektrizitätslehre mit Potenzial. LMU, München

Haagen-Schützenhöfer C, Burde J-P, Hopf M, Spatz V, Wilhelm T (2019) Using the electron-gas-model in lower secundary schools – a binational design-based research project. In: McLoughlin E, von Kampen P (eds) Concepts, strategies and models to enhance physics teaching and learning. Springer, Switzerland

Härtel H (2012) PdN-PidS 61(5):25–31

Herrmann F, Schmälze P (1984) Der math und naturw Unterricht 37(8):476–482

Muckenfuß H, Walz A (1997) Neue Wege im Elektrikunterricht. Aulis Deubner, Köln

Rhöneck C (1986) Naturwissenschaften im Unterricht Physik 34(13):10–14

Schumacher M, Wiesner H (1997) DPG-Tagungsband 1996:573–578

Schwedes H, Schilling P (1983) Physica Didactica 10:159–170

Schwedes H, Dudeck W-G, Seibel C (1995) PdN-PidS 44(2):28–36

Steinberg MS, Wainwright CL (1993) TPT 31(6):353–357

Urban-Woldron H, Hopf M (2012) ZfDN 18:201–227

Waltner C, Späth S, Koller D, Wiesner H (2009) In: Höttecke D (ed) GDCP Dresden 2009, vol 30. Lit-Verlag, Münster, pp 182–84

Wilhelm T, Hopf M (2018) In: Schecker H, Wilhelm T, Hopf M, Duit R (eds) Schülervorstellungen und Physikunterricht (Springer-Spektrum, Wiesbaden), pp 115–38