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First-year university students' conceptual understanding of electric circuits in relation to school and personal background

Abstract

This paper reports a quantitative study about university students' conceptual understanding of simple DC-circuits when entering first-year physics at a South African university. The aim was to investigate how conceptual understanding relates to the students' personal and school background. The conceptual framework was based on an existing model of the effectiveness of science education. Data were collected from 815 participants at a South African university. The conceptual understanding of DC circuits was measured in terms of performance in the well-known Determining and Interpreting Resistive Electric Circuits Concepts Test (DIRECT). Background information at school, classroom, and personal level was obtained with a questionnaire. Using Rash analysis, it was found that the students' conceptual understanding relates significantly to the type of school attended, home language, previous achievement, their attitudes towards physics, and gender. However, contrary to expectations, the students' conceptual understanding did not show a relationship with their exposure to practical work at school.

Keywords: *Science education, Conceptual understanding, DC-electric circuit, Contextual factors, South Africa*

1. Introduction

Concepts involved in the teaching and learning of electric circuits can be problematic to understand as these are highly abstract and complex (Mulhall McKittrick & Gunstone, 2001). Accordingly, students can generally solve quantitative circuit problems but cannot answer questions that require conceptual reasoning (Mbonyiryivuze, Yadav & Amadalo, 2019; McDermott & Schaffer,1992). Misconceptions about circuits have been found to be resistant to change, existing not only in school and university, but also amongst professionals (Stocklmayers & Treagust 1996). Therefore, it is important that university physics students should have good conceptual understanding of circuits as they represent the next generation of teachers, lecturers, scientists and engineers.

While there is an urgent need for science and technology development in the South Africa (SA), there is concern about the low levels of achievement at the school level. In 2017, only 26.8% of the public-school learners that wrote Physical Sciences in SA achieved 50% and higher, with Physical Sciences having the second-worst national performance pass rate out of the 11 key subjects, with Mathematics being the worst (Department of Basic Education [DoBE], 2018). However, poor performance should not be investigated in isolation as contextual and personal factors contribute to the poor results of South African learners in Science (Makgato & Mji, 2006, Ramnarain & Molefe, 2012). However, it is unclear how these factors relate to the conceptual understanding, as conceptual understanding cannot be guaranteed by performance (Jansen, 2012).

It is possible that contextual and personal factors influence leaners' and students' conceptual understanding of science. To investigate this possibility, the current study aims to relate university students' conceptual understanding of circuits to their school background and personal factors. Such understanding may assist in educational planning to design interventions that may support development conceptual of understanding amongst learners in different contexts. This may ultimately support the development of the next generation of scientists and engineers in SA.

The following research question was addressed:

> *How does first-year university students' conceptual understanding of DC-electric circuits relate to their personal and contextual factors in high school?*

Although the current paper on students entering university physics may indicate what they learnt at school, the issue of teaching and learning electricity at school level is a challenge beyond the scope of this paper.

2. Literature

The literature identified several contextual and personal factors that contribute to performance in general and particularly in the sciences (e.g. Creemers, 1994; Howie, Sherman & Venter, 2008; Lin *et al*., 2016; Makgato & Mji, 2006). Mwaba (2011: 2) indicated that

> … *school-based factors (the availability and use of teaching/learning facilities), socio-economic factors (the education of the parents and their economic status), student factors (motivation and attitude), school type, and teachers' characteristics are factors that contribute to learners' poor performance in the science subjects.*

Literature on the some of these factors are discussed below.

School type

In SA, learners attending rural and township schools are disadvantaged compared to learners from well-established schools in cities and towns (Howie, Sherman & Venter, 2008). During the apartheid regime in SA, schools in cities and towns were reserved for white learners. These schools had well equipped science laboratories and well qualified teachers. Schools in townships on the outskirts of cities, were allocated to 'non-whites' and were poorly funded and had poorly qualified teachers. After 1994, when democracy was introduced in the country, the city schools acquired multiracial learner populations, and continues to have good facilities. However, schools in townships continue to accommodate mostly learners from low socio-economic settings as found in poor communities and informal settlements. These schools still have poor facilities, overcrowded classrooms and a lack of equipment for practical science work, affecting learning negatively (Tshiredo, 2013). Independent schools generally have good facilities, well qualified teachers and learners from higher socioeconomic backgrounds.

Language

Wellington and Osborne (2001) pointed out that every science lesson is also a language lesson as science has its own unique language. Across the globe, much attention has been given to research in the language of science education, where English is not the most familiar language and yet is used as the medium of instruction for learners where it could be a second, third or even a foreign language (Lin, 2016). Apart from understanding the concepts of science, learners being taught in a second language have an additional problem interpreting the language of instruction or translating it into their home language.

In South African public schools, science instruction is offered in English and Afrikaans, but not in any of the other official languages such as isiZulu or Sepedi (Gudula, 2017). It is often argued that many scientific terms cannot be expressed in African languages (Hlabane, 2014) and that it is therefore not feasible to attempt to use African languages in science. African learners are consequently at a disadvantage in learning science.

In the 2016 Progress in International Reading Literacy Study (PIRLS), South African learners achieved the lowest mean scores, and the problem continues through to the secondary school level of education (Howie *et al.*, 2016). The poor reading levels are believed to be related to English being a second or third language for most of the South African population. McLeod Palane and Howie (2019) reported that learners from low socio-economic backgrounds whose language of instruction is English, despite it not being their mother tongue, perform better if instructed in English during the Foundation Phase, compared to those instructed in their mother tongue African languages. They, therefore, argue that learners who are instructed in their mother tongue African language during the Foundation Phase tend to be part of the most disadvantaged sector of the population. Typically, these learners attend township and rural schools, adding to the challenge of learning science in a second language to the developmental disadvantages at these schools.

Practical work

There are three broad purposes for engaging in practical work in science, summarized as the development of understanding the natural world, using equipment and understanding the processes of scientific inquiry (Millar, 2009). The first of these purposes is relevant in the current study as the focus is on the conceptual understanding of circuits.

Akuma and Callaghan (2019) point out that practical work is designed, presented and implemented inadequately in South African schools. Nevertheless, the DoBE (2011: 11) emphasizes the importance of practical investigations in science to "*strengthen the concepts being taught*". However, only one practical activity per term is compulsory, although the curriculum plans for various examples of investigations on each topic. This situation does not encourage teachers to prioritize constructivist practical work, as there is an urgency to cover the curriculum content for examination purposes (Lelliot, 2014). Muzah (2011) found that students are often coached for assessment while not allowed opportunities to explore ideas through practical activities and experiences with laboratory apparatus. Furthermore, a study on the pedagogical orientations shows that SA science teachers have a strong "active direct" teaching orientation overall, involving direct exposition of the science content followed by confirmatory practical work (Ramnarain & Schuster, 2014). As mentioned earlier, practical work is further compromised by poor facilities and lack of equipment in many South African schools, particularly in townships and rural schools. Such conditions prevent learners to explore scientific phenomena directly, as teachers are compelled to do demonstrations.

On the other hand, the value of practical work has also been questioned in the international arena. Sadler and Tai (2001: 131) found that "frequent laboratory experiments (including open-ended ones) did not predict increased college grades in physics". Earlier, McDermott and Schaffer (1992) found that conceptual development cannot be guaranteed even if students are exposed to "hands-on" activities when performing standard circuit experiments. These authors argue that when performing experiments, students predominantly learn laboratory skills, rather than being engaged on a conceptual level. It is therefore argued that conceptual understanding can be enhanced by cooperative group work and interactive engagement methods, such as "hands-on activities which yield immediate feedback through discussion with peers or instructors" (Hake, 1998: 2). These methods support students in overcoming their misconceptions (Crouch & Mazur, 2001; Gok, 2012).

Learner attitudes

Attitudes are mostly found to have meaningful correlations with science achievement (Abudu & Gbadamosi, 2014; Tekiroğlu, 2005). Once students experience a positive achievement, they will develop a positive attitude towards the subject. With these optimistic thoughts, they would be more willing and patient to attempt further studying, producing more positive results. Furthermore, a positive attitude would lead to an interest in the science (Osborne, Simon & Collins, 2003). This, in turn, would lead to commitment, which will likely contribute to academic success. Similarly, negative attitudes result in poor performance. Osborne *et al.* argued that many students perceive Physical Sciences as an irrelevant subject, dominated by equations and chemicals that they cannot relate to their everyday lives, resulting in poor performance.

Previous performance

Students tend to have certain perceptions about their past and expected future performances according to judgments about their marks (Tekiroğlu, 2005). Therefore, the previous achievement affects students' attitudes and hence their future achievement: High grades in Physics lead to continued high performance while poor grades tend to set the stage for further poor performance. Aggregated high school grades have been shown to be a good predictor of success at the tertiary level (Geiser & Santelices, 2007), while previous performance in specific subjects related to the intended study field may be better predictors of success. Previous performance in Mathematics is important not only because it is a prerequisite to study Physics, but because understanding mathematical procedures and concepts are essential in Physics. Also, performance in English may be an important predictor in South Africa due to the instruction in a second language for many South African students (Fleish, Schoer & Cliff, 2015.)

Gender

Since the early 1970s, there has been much focus on girls' underachievement in science, as males tend to outperform females. Girls' poorer performance in science has been ascribed to a general lack of interest in science (Koerting, 2018), often ascribed to gender stereotyping of scientists and roles traditionally expected of women. Particularly for electric circuits, Sencar and Eryilmaz (2003) found that males performed better on practical items; however, no significant difference in the theoretical items was noted. The accepted wisdom that boys perform better than girls is contradicted by Spaull and Makaluza (2019), who found that the National Senior Certificate (NSC) data of 2018 indicated that girls outperformed boys even in Physical Sciences. However, at achievement levels higher than 60%, boys performed better than girls in Mathematics and Physical Sciences.

Conceptual framework

From school effectiveness research, school and classroom environments and learners' personal situations and attributes are assumed to contribute to the effectiveness of learning (Creemer, 1994; Scheerens, 1990). In SA, Cho (2010) developed a conceptual model of effectiveness in science education to investigate variance in Trends in International Mathematics and Science Study (TIMSS) results. According to this model, learner outcomes are impacted by factors at school, classroom and learner levels. The learning climate, consisting of school, classroom, and student factors, is interactive and interrelated, contributing to learning effectiveness. Therefore, the model, shown in Figure 1, was selected and adapted to frame the current study.

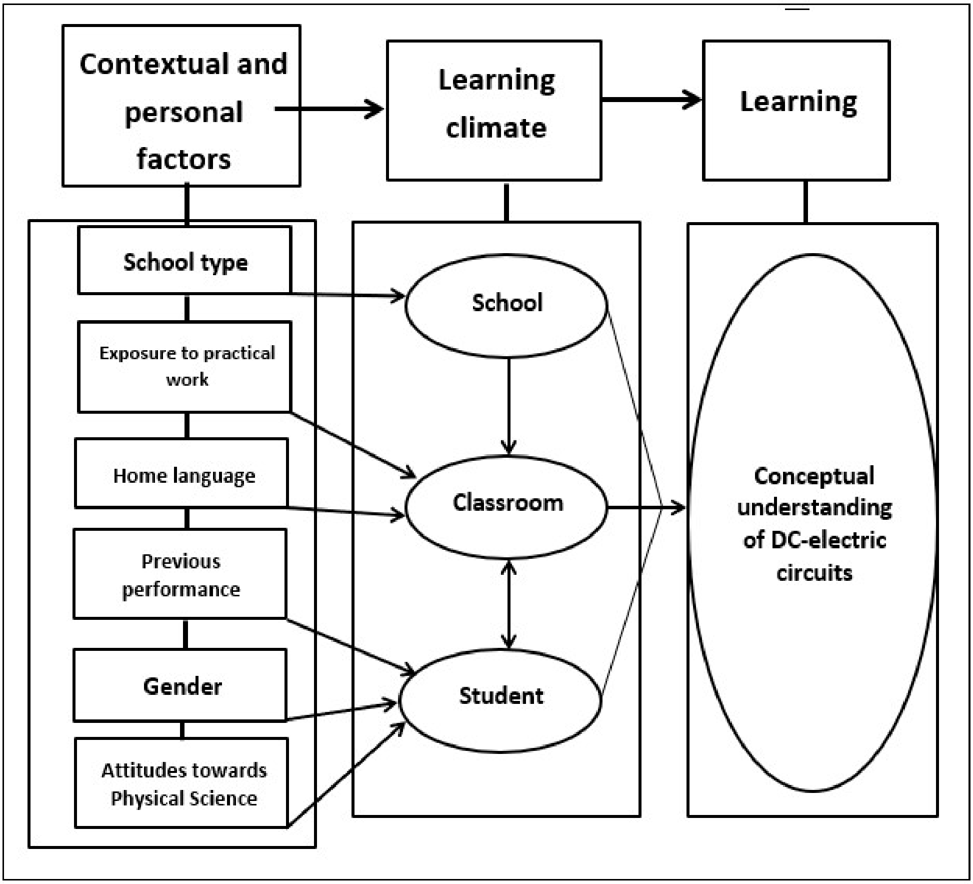

Figure 1: Conceptual framework showing contextual and personal factors at different levels contributing to conceptual understanding of DC electric circuits (Coetzee, 2021).

School type was used in the model as a single factor at the school level, as it largely represents the location and socio-economic status in the South African context. Although the home language may be considered a factor operating at each of the three levels, we regard it as operating primarily as a factor in the classroom, as most science learning and conceptual understanding development occur in the classroom. Also, at the classroom level, exposure to practical work was used as a factor. At the student level, gender, attitudes towards science, and previous performance are incorporated as factors that may contribute to students' conceptual understanding of DC-electric circuits. Some of these contextual factors may be interrelated as implied by the multi-level conceptual framework. For example, previous performance may influence attitudes and vice versa, while the school type may influence attitudes and exposure to practical work, and school type may be related to the home language. However, in the conceptual framework, the factors are grouped under the level where they are expected to influence the conceptual understanding of DC electric circuits directly.

3. Methodology

This quantitative study is located in the positivist paradigm, in alignment with the research question. The sample, consisting of 815 first-year students, was conveniently selected as they were enrolled for any of four first-year physics modules offered in different programs at a South African university. The admission requirements for each program are based on candidates' performance in Physical Science in the final school examination, as shown in Table 1. Due to the university's location in proximity to four provinces, the student population is diverse, including students speaking different African languages, English and Afrikaans as home languages. Furthermore, the student population is drawn from different types of schools, depending on the location of schools as well as socioeconomic background. Regarding gender, the sample included slightly more male than female students.

Table 1: Sample composition

Qualification	**Admission requirement (final school physics result)**	**Number of participants**
B.Eng.	70	490
B.Sc. (Physical Sciences)	60	92
B.Sc. (Biological Sciences)	50	142
B.Sc. (Extended Program)	50	91
TOTAL PARTICIPANTS 815		

Conceptual understanding was measured as the score obtained in the DIRECT-instrument which consists of 29 multiple-choice items. This instrument was shown to be reliable and valid (Engelhardt & Beichner, 2004) and has been used in many international studies (e.g. Karpatzianis & Kriek, 2012; Zimmerman, 2015). The biographical questionnaire consisted of structured, undisguised multiple-choice questions, presented in the same order and wording to all participants (Churchill, Brown & Suter, 1996).

Data were captured during normal class periods under test conditions; discussions between students was not allowed. The Rasch Unidimensional Measurement Model (RUMM2030) was used to analyse the data. The model places personal ability (measurement of performance in the test) and item difficulty on a single numerical scale so that the point on the scale that defines a person's ability is marked by the item that the person has a 50% likelihood of getting it correct (Wright & Mok, 2004).

4. Results and discussion

Validity and reliability

Even though the DIRECT-instrument was found to be a reliable and valid instrument in other contexts, its reliability and validity for the South African context had to be established. Before meaningful inferences could be made, we had to establish whether the instrument and sample fit the Rasch model. The *individual item fit residual* reflects the difference between the expected and the observed number of correct responses for a particular item. In the RUMM software, items are set to be flagged when the fit residual falls outside the -2.5 to 2.5 interval. Even though the mean item fit residual for this test and sample was 0.204, four items were flagged with fit residuals outside the accepted interval. Consequently, these items (questions 14, 16, 20 and 28) were excluded from the analysis to improve validity for the South African context. A detailed discussion of these items and why they were flagged were given elsewhere (Coetzee, 2021). Although this discussion falls outside the scope of the current paper, the reasons are related to the South African Physical Sciences school curriculum.

Another aspect that may threaten the validity of an instrument is that two or more items are measuring the same concept too closely, indicating that some items may be redundant. *Response dependence* was investigated for the instrument, and it was established that response correlation between items was acceptably low.

After the deletion of the four misfitting items, the degree of internal consistency reliability was calculated by Cronbach's coefficient alpha (α), which is most widely used for items with a range of possible options (McMillan & Schumacher, 2010). The reliability coefficient ranges from 0.00 to 1, and where the scale's coefficient is high, the scale is highly reliable, and vice versa. Values from 0.70 to 0.90 are acceptable (McMillan & Schumacher, 2010). In this investigation, the Cronbach coefficient value was 0.70, indicating a good model fit.

Contextual and personal factors

Investigation of unidimensionality and differential item functioning (DIF) in the Rasch model indicates the invariance of test items to contextual and personal factors such as those investigated in this study. The contextual factors mentioned in the framework were defined as person factors in the analysis. The RUMM software executes an ANOVA for each of the person factors. ANOVA is a parametric technique used to measure the variance, both within and between different groups per factor within a sample (Cavanagh, Romanoski & Fisher, 2005). In this study, the ANOVA, yielding F- and p-values for each person factor, was used to see if there is a meaningful difference in the performance of the different groups identified within each person factor. Such a difference would mean that the factor is important in predicting performance in the test. The F-statistic and the p-values obtained from the ANOVA for each of the factors are shown in Table 2.

Table 2: Summary of F- and p-values of all personal and contextual factors

Contextual factor	F-value	Probability
Type of school attended	12.02	< 0.05
Physical Science average	28.52	< 0.05
Mathematics average	32.69	< 0.05
English average	12.69	< 0.05
Home language	23.46	< 0.05
Exposure to practical work	1.21	0.31
Gender	56.26	< 0.05
Attitudes towards Physics	20.63	<0.05

The F-statistic value must be considered in combination with the p-value when deciding if the results are significant. A large F-value and a small p-value (<0.05) indicate that an item does not function similarly for all participants, indicating a relationship between that specific factor and the students' conceptual understanding of DC-electric circuits. Table 2 reveals p<0.05 for all personal factors except for "exposure to practical work", indicating that it is the only personal factor that did not contribute significantly to performance in the study.

A Person Frequency Distribution graph, such as Figure 2 (generated by the RUMM software) is a visual representation that compares the performance of different groups within the relevant person factor. The person location (on the horizontal axis) measures the participants' ability. A person with an average ability (0.00-person location) has a 50% chance of getting an item of average difficulty (at 0.00 item difficulty) correct. Each bar indicates the frequency of participants (on the vertical axis) at a specific location. The Person Frequency Distribution graphs indicate the mean and the standard deviation (SD) value for the particular factor in the display's top left corner. In the section below, results for each of the person factors are discussed.

Type of school

Figure 2 shows four types of schools, indicated in the questionnaire by participants, namely rural, township, city, and private schools.

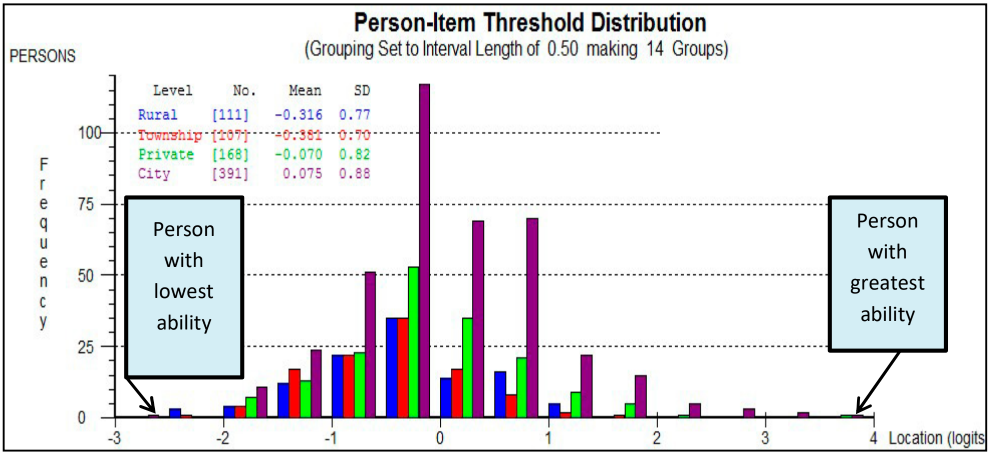

Figure 2: Person Frequency Distribution Graph for Type of School

Participants coming from city schools (mean location = 0.08; SD = 0.88) and private schools (mean location = - 0.07; SD = 0.82) performed better than participants from township schools (mean location = -0.38; SD = 0.70) and rural schools (mean location = - 0.32; SD = 0.77).

These results support du Plessis (2014), who argued that rural and township schools are characterized by various factors that negatively influence the quality of education.

Home language

The results indicate a significant difference in the performance of the different language groups. Figure 3 shows that Afrikaans home language speakers displayed the best test performance in the DIRECT-instrument (mean location = 0.18; SD = 0.82). On the other hand, students speaking any of the nine African languages (277 students) in SA as their home language displayed the weakest performance (mean = -0.41; SD = 0.64). This is not surprising as instruction in the home language is regarded as important for developing conceptual understanding in the classroom environment.

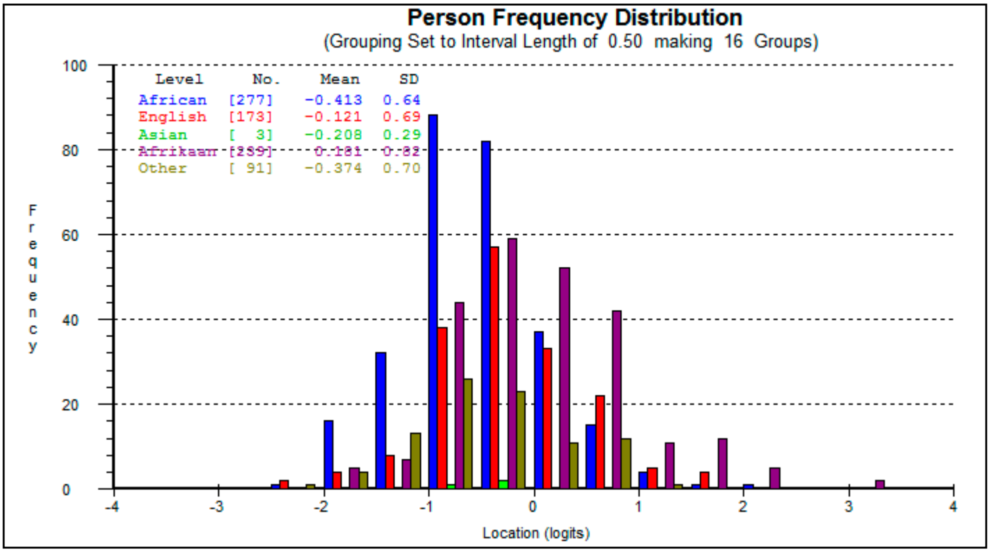

Figure 3: Person Frequency Distribution Curve for home language

This outcome supports Howie et al. (2008), who found that language proficiency in SA is a strong factor influencing science achievement since most of the students study science in a second or even third language. At the student level, many African learners may also have a disadvantaged background where many parents are illiterate due to poor education in the black population during the apartheid years. From a social constructivist perspective, home language plays an important role in the expression of understanding and concept development of scientific concepts and phenomena as scientific meaning is constructed through teachers' and learners' social practices (Fox, 2001).

Engagement with practical work

The options in the questionnaire, indicating how participants engaged with practical work at the school level, were: (a) Learners worked in small groups building circuits, (b) Teacher did demonstrations, (c) Teacher gave a reading from a book, (d) A travelling laboratory visited the school, and (e) Students visited another school/institution. Although students who were exposed to practical group work performed slightly better, with the highest person location mean of -0.11, the ANOVA indicated that the difference is not significant (Table 2 & Figure 4).

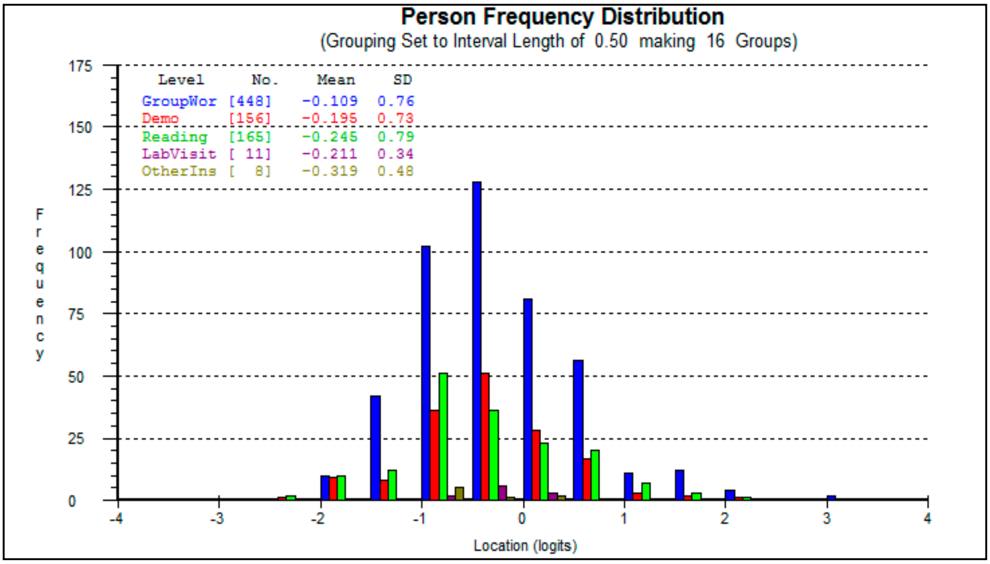

Figure 4: Person Frequency Distribution Curve for Practical Work

These results contradict the expectation that hands-on practical work would contribute to participants' conceptual understanding of electric circuits. The use of apparatus (even partially) in conducting science experiments is associated with developing cognitive and psycho-motor skills, which facilitates the logical process of education (Michaelides & Miltiadis, 2004). These results support McDermott and Shaffer (1992) as well as Ronen and Eliahu (2000), who argued that some misconceptions are so strong and resistant that even direct experience with the real phenomena may not always be effective in changing students' understanding.

Previous Performance

The results indicate a significant difference in the conceptual understanding of DC circuits for groups as predicted by high school performance. This is true for the three subjects that were investigated. These results are expected as the literature shows that high school grades tend to be a very good predictor of success at the tertiary level (Geiser & Santelices, 2007).

The results for Physical Science are shown as an example (see Figure 5). Students that achieved a Level 7 (80% - 100%) in their final Grade 12 Physical Sciences exam performed best in the DIRECT-instrument, while those who achieved a Level 3 (40% - 49%), displayed the weakest performance. Only the Level 7 participants achieved a positive mean person location (0.17) (Figure 5). All other participants had a mean person location below zero, which means they found the DIRECT-instrument challenging.

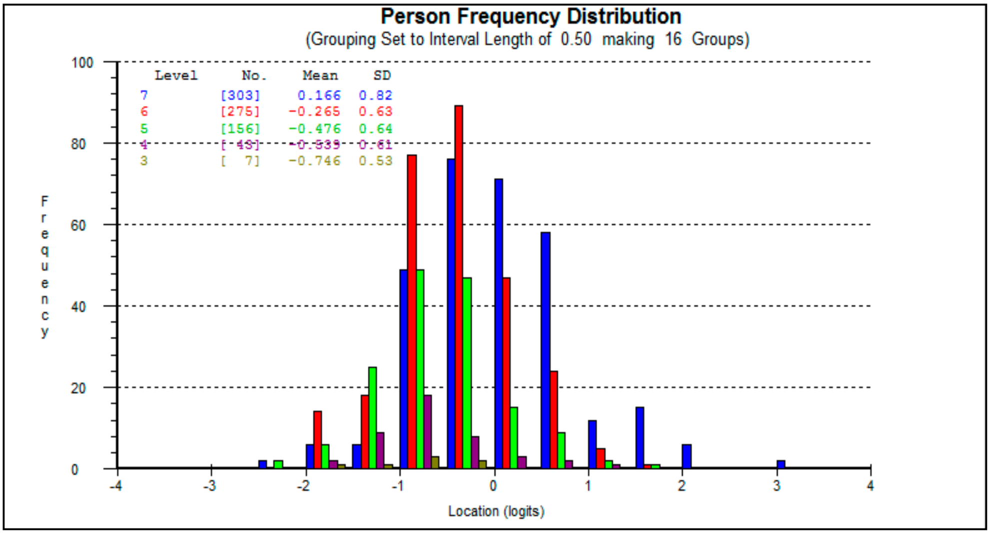

Figure 5: Person Frequency Distribution Curve - Physical Science average

For Mathematics, participants that achieved a Level 7 (80%–100%) in their final Grade 12 Mathematics exam performed best in the DIRECT- instrument with a mean location value of 0.15 and an SD-value of 0.78. Students that achieved a Level 4 (50%–59%) displayed the weakest performance (mean location = -0.62; SD = 0.59).

For performance in English, students achieving Level 7 (above 80%) in their Grade 12 year performed the best in the DIRECT-instrument, indicating a better conceptual understanding of simple DC-electric circuits. The sample of participants who achieved at Level 4 (50% - 59%) for English had the lowest average (mean location = -0.59; SD = 0.49). This emphasizes that proficiency in English supports South African learners' conceptual understanding of simple DC-electric circuits. This result underlines the negative effect of the situation where most South African learners do not have the privilege to use their home language to study and understand science conceptually (Probyn, 2004).

Gender

Figure 6 indicates that male participants (mean = 0.02 and SD = 0.8) displayed better conceptual understanding of simple DC-circuits compared to females (mean = -0.40 and SD = 0.59). In this study, 58.4% of the participants were male, 35.9% were female while 5.7% of the students did not indicate their gender when completing the biographical questionnaire.

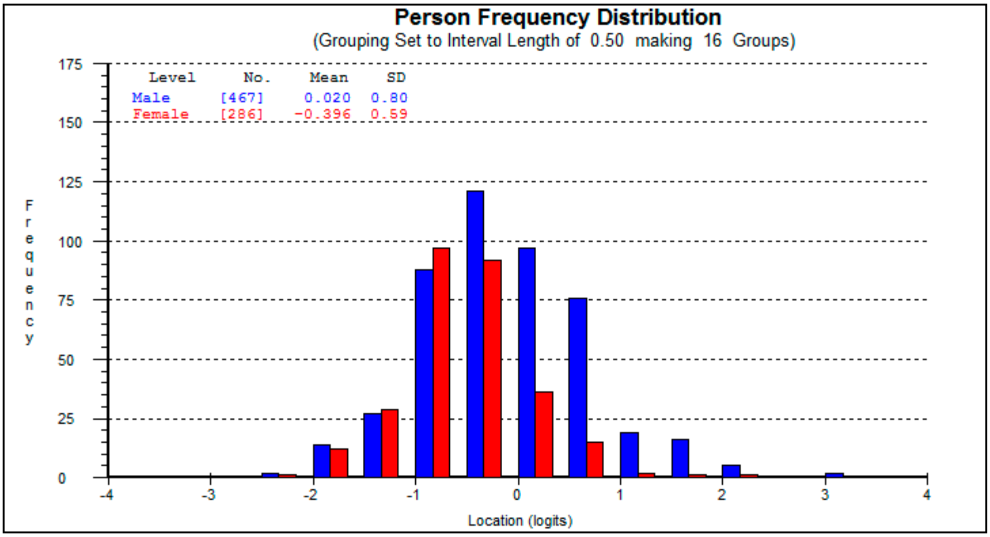

Figure 6: Person Frequency Distribution Curve for gender

Males showing significantly better conceptual understanding in this study aligns well with literature (e.g. Koerting, 2018) on gender in science performance. However, the sample was not homogenous, with the largest participating group of males in the engineering group having the highest minimum admission requirement (Table 1). This may have exaggerated the results on gender in science performance. However, the sample was not homogenous. The largest participating group were males in the engineering group (77%) which has the highest minimum admission requirement (Table 1). On the other hand, most of those who enrolled for Biological sciences were female. This may have influenced the results as the entrance requirement was highest for the engineering program (see Table 1). This selection pattern may result from how family and culture help shape gender relationships, as both males and females commonly perceive Physical Sciences and engineering courses as more masculine (Halpern *et al*., 2007).

Attitudes towards Physical Science

It is no surprise that students who like physics and who regard themselves as good in physics performed better (mean = 0.05 and SD = 0.78) (see Figure 7). Participants who did not like Physics and thought they were not good at it performed the worst (mean = -0.52; SD = 0.56).

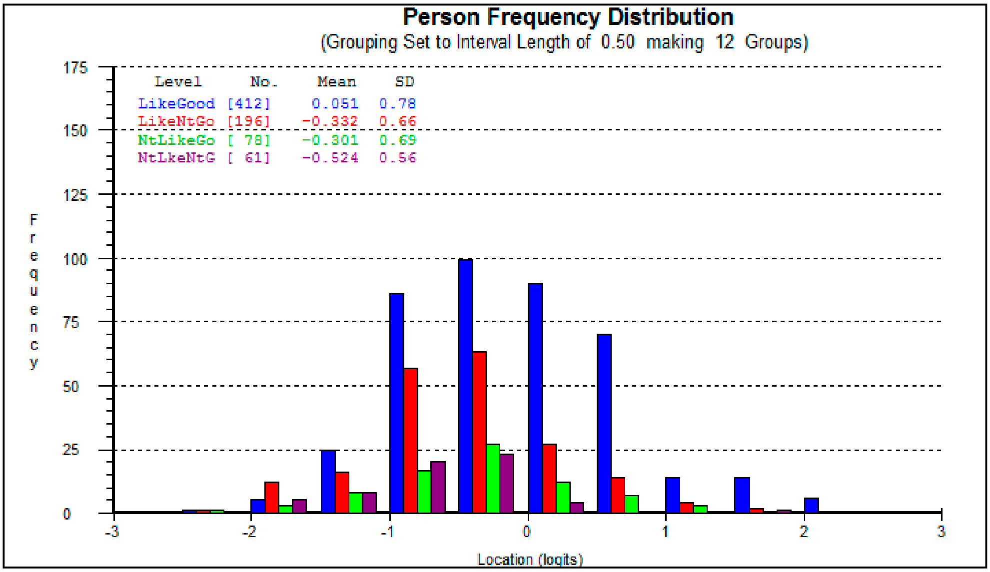

Figure 7: Person Frequency Distribution Curve – Attitudes Towards Physics

The result agrees with the researchers' shared vision that achievement and science attitudes are affected by each other and have a mutually supportive relationship (Tekiroğlu, 2005).

5. Concluding remarks

This study investigated how students' personal and contextual factors relate to conceptual understanding of electric circuits for students entering Physics at a South African university. However, our results are limited to the South African situation and should not be applied indiscriminately to other countries. Furthermore, our speculation about the causes of these relationships is not meant to claim causality.

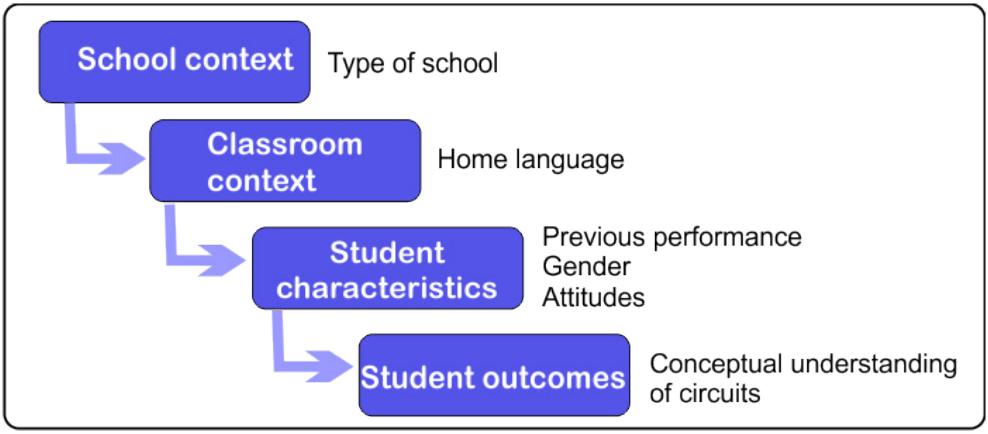

Figure 8: Learning contexts and student outcomes

It was found that conceptual understanding relates to school type, home language, gender, attitudes towards physics, and previous performance in Physical Sciences, Mathematics and English. These results agree with the literature findings regarding relationships between science outcomes and language (Lin, 2016), previous performance (Lin *et a*l., 2016), gender and attitudes (Osborne *et al*., 2003) The model presented in Figure 8 is based on the conceptual framework indicating how factors at school, classroom, and personal level may contribute to the outcome of students' conceptual understanding. The multi-level model emphasizes how school type lies at the basis of factors contributing to the conceptual understanding of circuits developed at South African schools. It is clear that that conditions in particularly township and rural schools continue to obstruct the development of scientists needed in the development of our country. We recommend that educational authorities develop and implement a comprehensive plan to support science education in township and rural schools.

An unexpected outcome of this study was the absence of a significant relationship between conceptual understanding and students' exposure to practical work at school, contradicting existing beliefs about the value of practical work in science (Hodson, 2014), providing scope for further research. The finding suggests that practical work in South African schools, even as group work, is not typically aimed at conceptual development but is of a confirmatory nature (Ramnarain & Schuster, 2014; Sadler & Tai, 2001). Therefore, we recommend that practical work include cooperative group work and interactive engagement methods (Hake, 1998) to enhance conceptual development.

The study highlights the language dilemma in South African science education. The advantage of mother-tongue instruction is clearly emphasized by the higher levels of conceptual understanding demonstrated by learners for whom Afrikaans is a home language, as these learners are usually schooled in Afrikaans. However, mother-tongue instruction is not feasible for the majority of learners, as discussed earlier. We concur with Rollnick's (2000) belief that a new language of science concepts must be learned to conceptually understand science. We, therefore, recommend more research into the development of learners' abilities to successfully study science in English as a second language.

Finally, we recommend further research to search for explanations of how each of these contextual factors is associated with conceptual development in science during the school years.

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