Creative Education, 2022, 13, 583-598
https://www.scirp.org/journal/ce
ISSN Online: 2151-4771
ISSN Print: 2151-4755

# Cognitive Skills in Adolescents' Self-Directed Learning Efficacy

**Õnne Uus*, Kadri Mettis, Terje Väljataga**

School of Educational Sciences, Tallinn University, Tallinn, Estonia
Email: *onne.uus@tlu.ee, kadrimet@tlu.ee, terjev@tlu.ee

**How to cite this paper:** Uus, Õ., Mettis, K., & Väljataga, T. (2022). Cognitive Skills in Adolescents' Self-Directed Learning Efficacy. *Creative Education, 13,* 583-598.
https://doi.org/10.4236/ce.2022.132035

**Received:** December 31, 2021
**Accepted:** February 15, 2022
**Published:** February 18, 2022



## Abstract

Hands-on science lessons to motivate and engage students as well as to enhance self-directed learning (SDL) have been suggested as the main goals of the 21st century through the knowledge-in-use perspective. Compared to conventional learning methods, SDL requires more advanced self-directedness and critical thinking skills applied by learners to conceptualize properly in sub-tasks to reach the relevant final conclusions. Achieving this requires one's sophisticated executive functions to choose the best alternative, because proper processing is enabled only by resisting mental distractions and inhibiting prepotent answers. The aforementioned skills, however, markedly vary among school students, as they are still in the stage of normal maturing. Thus, possible individual and gender-based differences among school-age learners should be studied more carefully, as the majority of the SDL suggestions have been given based on adult learners. To enhance scientific literacy and explore the learners' individual characteristics for that, we conducted a study of self-directed outdoor learning with school students aged 15 y (N = 82) examining their evidence-based concept construction in a real-life context. We measured: 1) participants' cognitive executive skills, and 2) their prior and post-knowledge levels; with both variables compared also by gender. The results showed differences in participants' knowledge acquisition trajectories and relations between their prior and post-knowledge as well as individual characteristics in predicting the outcome of self-directed learning (SDL). Further research on the heightened cognitive demand accompanying complex learning is needed in order to implement SDL efficiently.

## Keywords

Self-Directed Learning (SDL), Cognitive Executive Functions, Outdoor Learning, Cognitive Load, Prior Knowledge

## 1. Introduction

In our rapidly changing everyday lives, science applications are more than ever needed for orienting and reaching evidence-based conclusions (Aziz, Zain, Samsudin, & Saleh, 2014). To be prepared for that, education fosters hands-on scientific knowledge gain that is the core of 21st-century life-long learning to adapt flexibly (Lee, Tsai, Chai, & Koh, 2014). However, school students often lack two important aspects for this: 1) motivation, especially in adolescence age when their aspirations are formed (Zepeda, Richey, Ronevich, & Nokes-Malach, 2015); 2) prior domain-knowledge consisting of a) learning strategies for concept construction, and b) sufficiently advanced cognitive skills to handle a large amount of information concurrently (Schwaighofer, Bühner, & Fischer, 2017). Both require the handling of multi-level information in the focus of the human limited working memory (Engle, 2018) to gain the change in understanding (du Toit-Brits, 2018) to reach a proper final conclusion (Schwaighofer et al., 2017). This is needed to transfer content knowledge while learning: the execution of prior procedures and principles (or recalled prior concepts familiar to the present problem features) applied together to new problem resolving (Zepeda et al., 2015: p. 3). Thus, executive functions enabling students to resist distractions while encoding relevant units of information seem to be highly important especially in complex learning that itself is more loading for the learner (Schwaighofer et al., 2017) compared to conventional learning methods (de Bruin & van Merriënboer, 2017). Prior research has found that executive functions: the skills to monitor and manipulate information in mind (working memory) while suppressing distracting information and unwanted responses (inhibition) for flexible thinking (shifting between the different items) play a critical role in the development of complex learning proficiency (Cragg & Gilmore, 2014). Based on that, the current work investigates the relationships between school students' complex learning regarding scientific concept construction and the respective individual characteristics. We provide an illustrative example of the prior work on multidimensional reciprocity of the executive skills (**Figure 1**) in complex learning, where the dashed lines represent relationships that change over the course of human development.

What makes science learning complicated is that young students often lack critical thinking competency for scientific argumentation: the ability to understand principles (theories, and laws about a scientific issue); the skills to use correct epistemology (for evaluations); also the capacity (a) to construct, and (b) to communicate one's own knowledge (Faize, Husain, & Nisar, 2017). As it requires conceptual thinking (Dörrenbächer & Perels, 2016) that is based on constant adjusting of attention (Francom, 2010: p. 31), it necessitates certain aspects not fully matured yet in novice learners: 1) Not to lose sight of the aim (to continue to pursue the goal) while combining disparate units of information—the process, which requires advanced working memory capacity and executive functions ensuring that only task-relevant (not irrelevant) information will be processed (Shipstead,

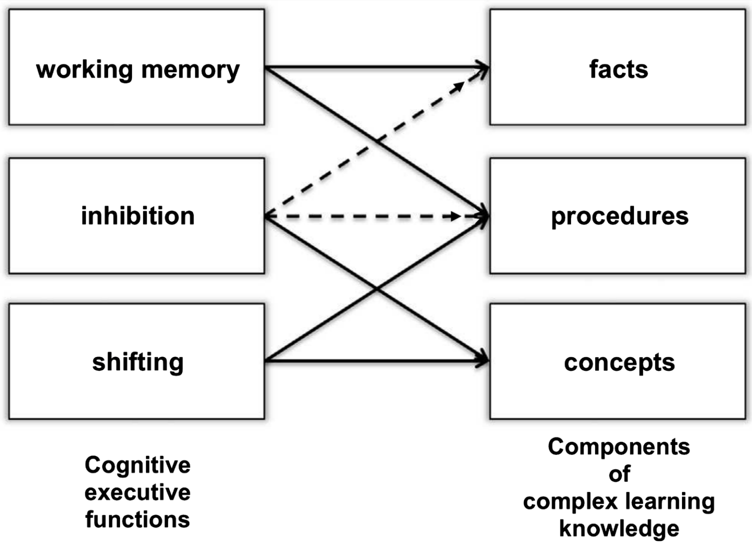


**Figure 1.** The theoretical framework of the cognitive executive functions in complex learning was adopted from Cragg & Gilmore (2014).

Harrison, & Engle, 2015). 2) Carrying out the sub-tasks at the same time requires a high level of metacognition to maintain all the mental acts (Roebers, 2017). However, if the cognitive load is too high and directly impairs one's conceptualization (Janssen, Kirschner, Erkens, Kirschner, & Paas, 2010), it severely hampers deep learning (Butcher & Sumner, 2011).

**Research problem**

As complex learning is grounded in the learner's simultaneous requirement to keep a set of relevant information items in mind while managing other learning activities, it is more demanding than conventional learning methods (De Bruin & van Merriënboer, 2017) where cognitive overload is a high risk (Kirschner, Sweller, & Clark, 2006), as the human cognitive capacity is able to process efficiently only a small amount of concurrent information held active in a short period of time (Cowan, 2014). Hence, the executive functions during the cognitive-constructive activity (Davidson, Amso, Anderson, & Diamond, 2006) are particularly needed to resist irrelevant items (e.g., too many learning tasks, one's own ideas not needed at the moment yet interrupting the processing or a social noise caused by the peers) in order to deal only with relevant information (Schwaighofer et al., 2017: p. 62). This kind of co-work of executive functions is truly difficult especially in children (i.e., continually resetting when the task changes) because from a developmental perspective it has a long progression towards the final maturity (Davidson et al., 2006). Thus, in performing complex tasks the high and low-capacity individuals differ greatly (Engle, 2018; Rutherford, Buschkuehl, Jaeggi, & Farkas, 2018; Sweller, van Merriënboer, & Paas, 2019). This paper aims to investigate the self-directed concept constructions using the venue of scientific outdoor learning, where hands-on participants can draw conclusions based on evidence, make decisions about the natural world, and consider the human-made changes directly influencing nature (OECD-PISA, 1999). The problem in this process might be related to the heightened cognitive load (compared to the teacher-directed method) that can hamper resisting distraction (Rutherford et al., 2018) for the transfer of knowledge (Sweller et al., 2019; Young et al., 2014; Zepeda et al., 2015) to reach a proper conceptual conclusion (du Toit-Brits, 2018). This new outdoor learning scenario can open the different corners of the cognitive demand accompanying complex SDL allowing us to explore the respective individual differences. Prior work highlights the need for empirical studies with adolescence age samples encompassing, in addition to the abovementioned aspects also the developmental spurts of puberty that can also have an impact on the learning progress while the initial conceptualization of the SDL method (and suggestions on this) is based on adult learners (Schweder & Raufelder, 2019).

## 2. Theoretical Background

As in any learning method, especially in the SDL context, the learner's executive functions that support the working memory processing during his/her cognitive-constructive activity (Reio & Davis, 2005) enable to manipulate only relevant information (Schwaighofer et al., 2017: p. 62). The latter is challenging especially for novice students because of the need to integrate new information with the already existing one (Zepeda et al., 2015) i.e., to reorganize prior knowledge that in children reveals the complexity of even apparently simple events, as they do not have yet as much experience as adults have (Gredler, 2012). For the same reason, some school students often accused of "not trying enough" are those with low capacity of working memory and executive functions interrelation, thus they are not able to follow instructions, use resources, and make conclusions (Cowan, 2014). Still, as learners are active participants in the learning process, which means they are constructors of knowledge (not passive recipients of information waiting to be filled with knowledge), young students' individual agency should be scaffolded properly (Zepeda et al., 2015) to keep the cognitive burden of the learners low in order to help to integrate prior and new knowledge, and learn to act on it (Hadwin & Oshige, 2011: p. 241).

### Developmental Aspects in SDL

Developmental neuroscience suggests that brain functioning capability for complex processing passes a prolonged developmental path of the maturing course (Lee, Bull, & Ho, 2013; Nęcka & Lulewicz, 2016). The human prefrontal cortex (that directly facilitates the cognitive processes) matures as the last area of the brain, taking place in late adolescence or early adulthood (Anderson, 2002; Reio & Davis, 2005). This causes significant individual differences in school students' cognitive skills due to the varying maturing speed (Best & Miller, 2010). Thus, the fundamental cognitive functions (attention adjustment; abstraction, comparison, and differentiation, which are all multilevel psychological processes) are not to be simply "taken on" but are possible when they get sufficiently advanced

(Vygotsky, 1994: p. 356). Without the needed capability but still forced to contribute all the energy trying to make sense of the learning material (Butcher & Sumner, 2011), students experience that multi-level complex tasks often add an overburden, which as a circle back restricts one's executive control to grasp only the relevant info-items to be processed (Best & Miller, 2010). This can lead to inadequate conceptions (or fake concepts construction) about the phenomena (Duit, Treagust, & Widodo, 2008). The particular period is adolescence, as in this age the prefrontal cortex (that plays the most important role in executive functions' spurt), together with the frontal lobe remarkably increases its white matter volume due to the advanced myelination that covers the axons. This aspect fosters rapidity in the transmission between the nerve-cell (Uytun, 2018) and makes the processing more efficient (Blakemore, 2012). At the same time, cognitive control functions, however, are also related to the pubertal hormonal processes, thus influencing the learning progress of boys and girls differently (Delevich, Thomas, & Wilbrecht, 2018; Schweder & Raufelder, 2021). E.g., boys (compared to girls) are found to use fewer control strategies in their learning (Schweder & Raufelder, 2019) due to the fact that in adolescence age the normal developmental maturation rhythm of cognitive control sophistication generally lasts longer in boys than in girls (Weber et al., 2021). Yet, girls, in general, prefer learning in the familiar settings (rather repeated and "secure" methods) not challenging them, and also relatively collaborative work formats (together with others); while boys enjoy challenges (preferring autonomous exploring around and discovering new things) not practiced before (Liu, 2009). According to Vygotsky and Piaget suggesting that one's social interaction is the root of his/her cognitive development when working together: the group serves "as a teacher"; the group shapes a medium helping to solve the tasks (Stöckert & Bogner, 2020), where individual responsibility and positive interdependence improve the whole group's outcome (Roger & Johnson, 1994: p. 2). Thus, it seems that such a "collective working memory" that enables sharing the individual cognitive load (Paas & Sweller, 2012) might have a beneficial impact on girls (who prefer group learning, Liu, 2009). Lower cognitive load allows one to act based on choice, not on impulse, thus preventing inappropriate responses and acts (Davidson et al., 2006).

**Current work**

Involving SDL phases: planning, exploring, synthesizing, and making conceptual conclusions, we designed an autonomous science learning scenario. The aim of the participants' activity in this experiment was to learn in small groups (consisting of 3 - 4 participants) about a real-life environment, namely cover-, and bare-seed plants grown in different circumstances (i.e., determine different conifers and deciduous trees: near the traffic and in a park) by gathering data, analyzing, and making conceptual conclusions based on scientific evidence. Before the outdoor learning task, we also detected learners' individual cognitive executive capacity (i.e., inhibition to resist distractions in processing) using the *Fruit Stroop* task (by Meixner, Warner, Lensing, Schiefele, & Elsner, 2019) that was adapted into Estonian for the current experiment. The rationale to involve this tool is based on prior work saying that both working-memory capacity as well as the cognitive executive functions (in order to find the "right" response one needs to inhibit the automatic or "wrong" ones) largely vary among young students (Nęcka & Lulewicz, 2016). Our ultimate goal was to find out the relations between school students' individual characteristics: cognitive executive skills, knowledge level, gender, and their SDL outcome. The current experiment was organized as a part of a more extensive research study on innovative approaches to learning and teaching outside the classroom supported by technology.

**Research question and hypotheses**

We were seeking answers to our main research questions: *Do we see any relations between the students' prior and post-knowledge? How do novice school students' cognitive executive skills interact in complex SDL? Are there gender differences in learning outcomes?* Hypotheses are as follows:

H1: *There will be differences in participants' knowledge acquisition trajectories.*

H2: *The higher one's pre-knowledge, the higher his/her post-knowledge gained in SDL.*

H3: *The individual characteristics predict the outcome of SDL.*

## 3. Method

### 3.1. Participants

The participants of the study were school students, N = 82, aged ~15 y (Grade 8) from 4 different classes of three ordinary municipal schools in Tallinn, Estonia. Participation in the study was entirely voluntary. We decided to choose this age group for the following reasons: as in this age (of adolescence) the students are often unmotivated to learn science (Zepeda et al., 2015), thus the scenario (used in this work) may attract them. In this age group, the normal developmental spurts of puberty can reveal more clearly the differences among adolescents.

***Inclusion criteria.*** Although there was a larger sample size (94) of eighth-graders taking part in this outdoor-learning experiment, it turned out that a large proportion of students had not completed all; and/or answered all the questions; and/or did not provide their correct personal identification code they were asked to create at the beginning of the experiment (authentic combination of letters of one's name and numbers of the date of birth) and used also in each of the next sub-tasks. Therefore, as we could not relate all the sub-tasks (due to the aforementioned missing aspects), we included in this work only the data of those students who had marked the correct identification code in all the sub-tasks, answered all the questions, and completed all the tasks. The final number of participants was 82.

### 3.2. Research Instruments and Data Analysis

1) *Fruit Stroop task*

Colored rectangles present fruits in their correct colors, fruits in black and white, and fruits in incorrect colors, while participants were asked to "learn" and click on a respective color (as quickly as possible), the *Fruit Stroop* task requires the suppression of the automatic or dominant response (i.e., clicking on the colors one sees). The time on clicking (the correct colors on each page), and an interference score were calculated automatically by the task (Meixner et al., 2019). The "*Stroop effect*" (which appears if automatic behavior interferes with the processing) links to inhibitory control, whereas the Fruit Stroop task also involves the working memory aspect, necessitating the rule to be kept in mind and recalled properly as well as the appropriate fruit colors (Archibald & Kerns, 1999). The higher interference score indicates one's lower inhibition ability (r = 0.78) (Meixner et al., 2019). We implemented this Fruit Stroop task as a web-based application of JSPsych (De Leeuw, 2015). Time in seconds (spent on clicking correctly), and an interference score were calculated automatically by the application (Meixner et al., 2019) that reveals a *Stroop Effect* when an automatic behavior occurs that interferes with one's processing related to one's weaker executive function as a system: the inhibitory control together with the working memory contribution (i.e., a proper performance needs the right rule to be kept in mind) to push the right button (Archibald & Kerns, 1999). The higher the negative value in the *Fruit-Stroop* task interference score, the lower one's inhibition ability (r = 0.78) (Meixner et al., 2019).

2) Semi-structured questionnaires about a) participants' pre-knowledge (i.e., before the outdoor-learning), and b) post-knowledge (i.e., after the outdoor-learning scenario). Participants' knowledge levels were analyzed and coded based on Heddy, Danielson, Sinatra, & Graham (2017) operationalization of conceptual change referring to the process of restructuring conceptual knowledge about a phenomenon from non-scientific views towards accepted scientific perspectives respectively:

"1" the student has an inaccurate or misconception

"2" a hybrid conception that mixes misconceptions with an accurate understanding of the concept(s)

"3" an accurate but underdeveloped understanding of the concept(s) (1 relevant explanation)

"4" an accurate but developed understanding of the concept(s) (2 relevant explanations)

"5" a well-developed and nuanced understanding of the concept (3 or more relevant explanations).

The coding was done by two researchers to avoid possible differences, Cohen's kappa value (between the two researchers' estimations) was 0.9 (Asymptotic Standard Error: 0.03; Approximate Tb: 17.7; $p < 0.001$), which shows that the validity was good (i.e., near-perfect agreement). After coding the participants' results, the data analyses were conducted with the Spss and R-Studio statistics programs.

### 3.3. Procedure

1) The *Fruit Stroop* task was conducted in participants' everyday classroom,

where the students were asked to find a place in this room at separate tables each equipped with a tablet. We provided verbal instruction, demonstrated how to generate a personal ID-code (for anonymity of the data) and how to perform the *Fruit Stroop task*. The session lasted approximately 15 minutes.

2) Participants answered the pre-knowledge questionnaire in the same room. After finishing the latter, participants were divided into groups to be prepared for the SDL task outdoors (mainly consisting of 3 group-mates).

3) In the outdoor tasks, the participants gathered and analyzed real-world data in order to draw their scientific conclusions. Each group followed a predefined path with different location points to carry out necessary observations and measurements if needed. The researchers' task was to follow the students in their activities remotely (and be there if needed) without direct intervention.

Permission from the school director, then the science teacher was asked. Participation in the learning event was voluntary and was decided by the teacher of this class. We sent a letter to the parents asking for their consent (to allow their children to participate in the study), where we described the study and its aim, data management, also ensured confidentiality as well as no harm caused to the students. Participants provided their personal consent while they entered the experiment. We also informed them that they can quit at any time.

## 4. Results

We first present an overview of the participants' conceptual knowledge levels (descriptive is given in **Table 1**). The proportions by gender were as follows: 43 boys (52%), and 39 girls (48%). The average levels of participants' pre- and post-knowledge (**Table 1**) were statistically different $t(80) = 4.4998$, $p < 0.001$ (p-value = 2.28e−05).

We next analyzed the trajectories of the participants' knowledge level change. It turned out that in the case of most students it improved, but there were also individuals whose post-knowledge result decreased (i.e., their change was negative with the dynamics that show lowering). A paired t-test showed a statistically significant difference between those two dynamics, $t(81) = -7.2366$, $p < 0.001$ (p-value = 2.348e−10). We call this change *delta*, which shows $\Delta(82) = 66\%$ increased; $\Delta(82) = 22\%$ remained the same, and $\Delta(82) = 12\%$ tended to decrease instead of increasing (that was assumed to happen). H1 (*There will be differences in participants' knowledge acquisition trajectories*). We examined also a correlational relationship between the participants' pre- and post-knowledge levels. Pearson's product-moment correlation analysis showed a strong correlation $r = 0.5$ ($t = 4.4998$, df = 80, $p$-value = 2.28e−05; cor: 0.4494257). Based on this outcome

**Table 1.** The descriptive of participants' knowledge levels.

| | N | M | SD | range | skewness |
|---|---|---|---|---|---|
| Pre-knowledge | 82 | 2.15 | 1.48 | 0 - 6 | 0.72 |
| Post-knowledge | 82 | 3.48 | 1.65 | 0 - 6 | −0.27 |

we can say that the higher the learner's pre-knowledge, the higher his/her post-knowledge level (that he/she had gained during the SDL scenario). H2 (*The higher one's pre-knowledge, the higher his/her post-knowledge gained in SDL*) was confirmed. We next examined the participants' knowledge levels regarding the variable gender (**Figure 2**). We see that the final conceptual knowledge improved more efficiently in girls than in boys. The Two-Sample t-test showed $t(79.996) = -2.2384$, $p < 0.05$ (p-value = 0.02798).

The simple linear regression model where the level of post-knowledge (dependent variable) was analyzed by the static (independent) variables: 1) pre-knowledge, 2) *Fruit Stroop* result, and 3) gender showed that the model is statistically significant $F(78) = 12.5$, $p < 0.001$ (p-value: 9.311e−07); it's predictive power R = 0.324 is relevant describing 32% ($R^2 = 0.299$) of the variance, and all the predictors (i.e., independent characteristics) are also significant (**Table 2**).

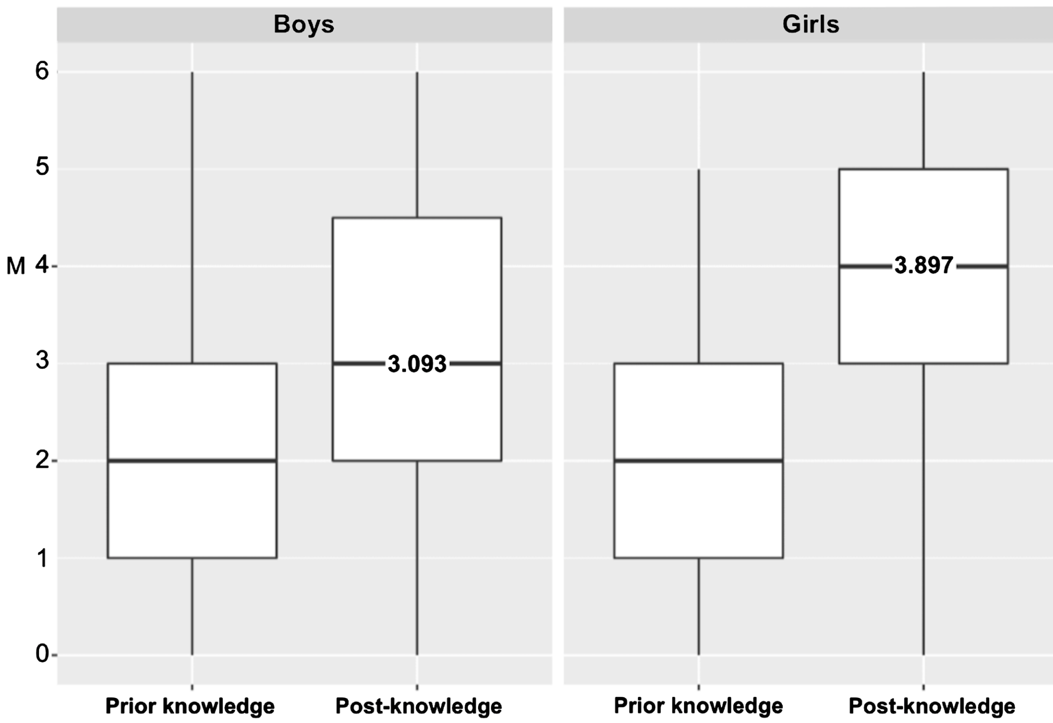


**Figure 2.** Participants' prior and post-knowledge levels by gender (N = 82).

**Table 2.** Regression model results.

| Independent characteristics | $\beta$-value | $p$-value |
|---|---|---|
| Prior-knowledge level | $\beta = 0.5559$ | 1.23e−06*** ($p < 0.001$) |
| Gender girl | $\beta = 0.8863$ | 0.00582** ($p < 0.01$) |
| The *Fruit Stroop* score | $\beta = 0.1721$ | 0.03214* ($p < 0.05$) |

Significance codes: ***0.001; **0.01; *0.05.

We also aimed to establish whether there is an interaction in the case of gender. It turned out that there was no interaction (in both cases, the logic was the same, and the result was valid as shown in **Figure 3**).

Based on the outcome of the regression analysis that clearly shows the significance of the combination: one's prior knowledge, cognitive executive skills, and gender. It can be said that the higher score in the cognitive skills ($p < 0.05$) predicts a higher level of post-knowledge gain. We also see that gender ($p < 0.01$) predicts a higher level of post-knowledge gain in girls, allowing us to say that girls learned better than boys. H3 (*The individual characteristics predict the outcome of SDL*) was confirmed.

## 5. Discussion

The current work investigated adolescent-age school students' scientific concept construction and explored the aspects of individual characteristics for that. We found that the conceptual knowledge of most of the students increased as a result of the given SDL assignment. However, for many of them, the knowledge level stayed the same (as prior to the outdoor learning episode) or even decreased. This allows us to say that H1 (*There will be differences in participants' knowledge acquisition trajectories)* was confirmed. It also turned out that the participants' prior and post-knowledge levels were correlated. Based on our first RQ (*Do we see any relations between the students' prior and post-knowledge?*) the latter finding is in line with previous findings: prior knowledge contains in addition to the basic factual domain-knowledge also the learning strategies for concept construction requiring thus sufficiently advanced cognitive skills to handle a large amount of information concurrently (Schwaighofer et al., 2017) H2: *(The higher one's pre-knowledge, the higher his/her post-knowledge gained*

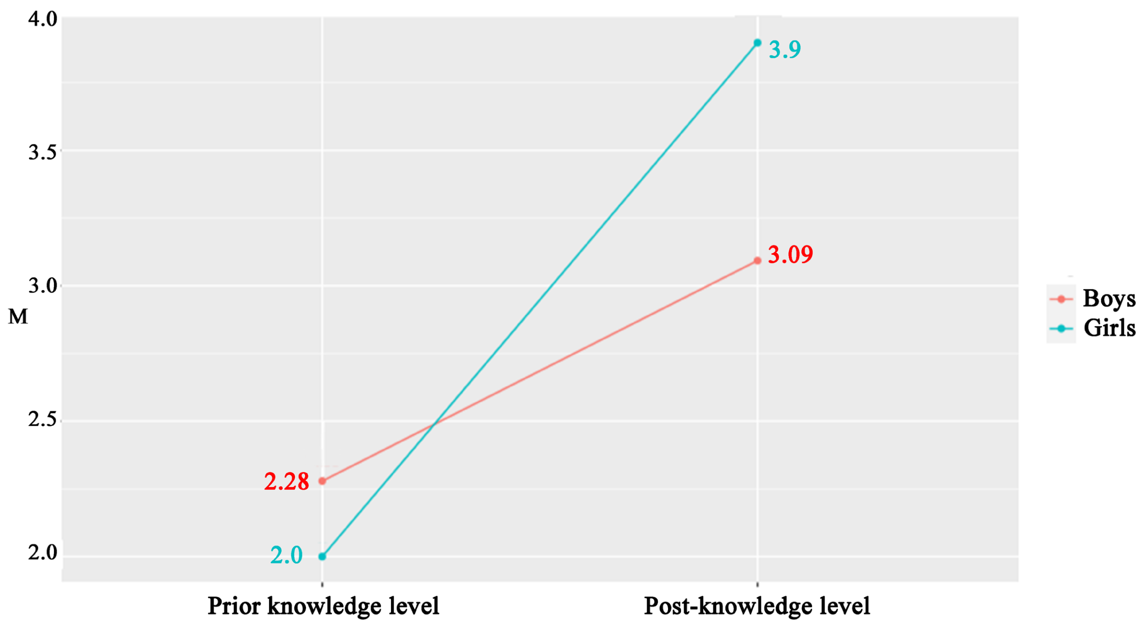


**Figure 3.** Interaction control by gender in participants' gained knowledge (N = 82).

*in SDL)* was confirmed. Based on our second RQ-s (*Are there gender differences in learning outcomes?*) it came out that a higher level of post-knowledge was gained by girls than by boys. This finding relates to prior work that female students at adolescence age (compared to male students of the same age) have greater willingness to put the effort into their learning process, while boys (compared to girls) are found to use fewer control strategies (Schweder & Raufelder, 2019). Based on our third RQ-s (*How do novice school students' cognitive executive skills interact in complex SDL?),* the significance of the cognitive executive functions was revealed. This also directly relates to prior studies: as SDL necessitates constant shifting (from one subtask to another as well as from one strategy to another), it needs to avoid distractions (Schwaighofer et al., 2017) to mentally excerpt and "put on hold" a relevant part of the information (Rutherford et al., 2018). The executive "controller" enables to highlight and process only the needed info-items in order to memorize the relevant information (Nęcka & Lulewicz, 2016), which is needed for two reasons: firstly in initial encoding and relating the new and prior knowledge for drawing a conclusion in one's mind in order to make a choice (among alternatives) and release the relevant (right) answer or behavioral act, and secondly, at the same time it also needs to inhibit the automatic or wrong response (Cragg & Gilmore, 2014; Engle, 2018). In this process, however, also the working memory is fundamental because it enables one to recall appropriate responses (not the quickest one) by keeping respective rules of present relevance in mind (Archibald & Kerns, 1999). Yet, both of them, the working memory as well as the executive abilities of children, follow prolonged maturity paths throughout their development—the aspect that causes considerable individual differences in a "co-work" between the working memory and inhibition (Anderson, 2002; Best & Miller, 2010; Davidson et al., 2006; Lee et al., 2013; Nęcka & Lulewicz, 2016). Thus, in performing complex tasks the low- and high-capacity individuals differ greatly (Engle, 2018; Rutherford et al., 2018; Sweller, van Merriënboer, & Paas, 2019) because without the needed capabilities the multi-level processing often adds an overburden, which as a circle back restricts one's executive control to handle only the relevant information (Best & Miller, 2010). H3 (*The individual characteristics predict the outcome of SDL)* was confirmed. Due to the fact that in SDL there is required to carry out (a) the mental encoding-retrieval interactions as well as (b) all the physical activities regarding one's hands-on learning, thus, the cognitive load of the individual learner (in performing the two types of operations) is even higher. Based on prior work (Cragg & Gilmore, 2014) and the current work empirics we propose the following hypothetical model (**Figure 4**) of the contribution of the cognitive executive functions in the complex SDL method context.

In light of this, another aspect of the small group work (that was used also in the present experiment) should be studied in more detail in the framework of complex SDL. On the one hand, prior work suggests that the group can help the individual learner to lower one's own cognitive load (Paas & Sweller, 2012). Yet,

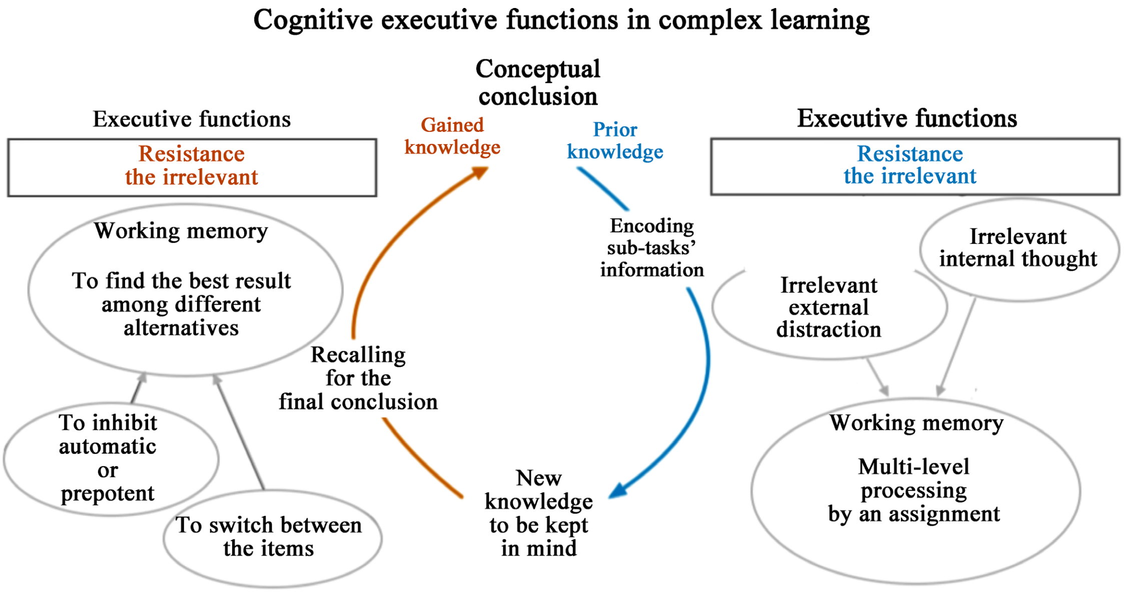


Figure 4. The model of cognitive executive functions in complex SDL.

on the other hand, might it be as an additional load i.e., an irrelevant external distraction interrupting the individual encoding (in an already high load condition accompanying complex learning)? Multitasking may intervene in one's own processing, and when seeking help it can distract also fellow students, which, as a result, complicates the whole group's learning (Heflin et al., 2017). Those aspects we open in our next study, where we aim to explore in more fine-granted the pros and cons of collaborative learning while novice students practice their independent scientific knowledge construction. Our ultimate aim is to develop the scaffolding strategies respective to an individual learner's needs to perform efficiently in a complex learning context, which (a) won't overload the young students, but rather keep their motivation to study science, and (b) would enhance the effective implementation of the SDL paradigm among school-age learners not fully matured yet.

## 6. Conclusion

Based on prior work and the current results, it can be concluded that we cannot take for granted that when implementing the complex SDL approach, all school students (even at the same age group) are skilled and sufficiently capable of coping equally with the necessary steps while constructing their new knowledge. Especially components of planning, monitoring, and evaluation of one's own learning all together increase the requirement for learners' advanced cognitive skills and sophisticated metacognition, which, first of all, need to be taught, scaffolded, and practiced (Zepeda et al., 2015). These are particularly important suggestions within the SDL paradigm, and also for autonomous learners in general due to the increased need for distance-learning as an inevitable educational approach through widespread restrictions caused by the global pandemic situation. All those aspects challenge especially novice school students with not fully matured yet the self-regulation and SDL skills to handle piles of multi-level information on their own that often result in not quality learning like superficial or fake knowledge, inadequate argumentation, and loss of motivation to continue improving one's knowledge.

## 7. Limitations and Future Research

Although the present work focused on the adolescent population, a critical period, when motivation tends to decline, further research is required to generalize these results to younger or older learners as the final maturing course of human cognitive skills continues to develop into adulthood. Notwithstanding the small sample size (as a negative side of our work), we as educational psychology researchers call for further studies to continue the work and discussions on today's school students' optimal cognitive load in order not to overburden them in complex learning circumstances. Instead, there is a desire to keep learners motivated with adequately challenging, yet attractive, and at the same time age-appropriate demands in order to prepare them for independent problem solving according to the 21st-century educational strategy, to make proper decisions in the multi-information environment, while also staying mentally healthy and continuing with lifelong learning giving them an advantage for quick reorientation in the rapidly changing circumstances of contemporary life around us.

## Acknowledgements

We are greatly thankful for all the school students taking part in this study. This project is partially funded by the European Union's Horizon 2020 Research and Innovation Programme, grant agreement No. 669074 and No. 856954, and by the project, TU TEE, Tallinn University as a promoter of intelligent lifestyle" (nr 2014-2020.4.01.16-0033) under activity A5 in the Tallinn University Centre of Excellence in Educational Innovation. This research project is supported by Tallinn University School of Educational Sciences Research Fund.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

## References

Anderson, P. (2002). Assessment and Development of Executive Function (EF) during Childhood. *Child Neuropsychology, 8,* 71-82. https://doi.org/10.1076/chin.8.2.71.8724

Archibald, S. J., & Kerns, K. A. (1999). Identification and Description of New Tests of Executive Functioning in Children. *Child Neuropsychology, 2,* 115. https://doi.org/10.1076/chin.5.2.115.3167

Aziz, M. S., Zain, A. N. M., Samsudin, M. A. B., & Saleh, S. B. (2014). The Effects of Problem-Based Learning on Self-Directed Learning Skills among Physics Undergraduates. *International Journal of Academic Research in Progressive Education and Development, 3,* 126-137. https://doi.org/10.6007/IJARPED/v3-i1/694

Best, J. R., & Miller, P. H. (2010). A Developmental Perspective on Executive Function. *Child Development, 81,* 1641-1660. https://doi.org/10.1111/j.1467-8624.2010.01499.x

Blakemore, S. J. (2012). Imaging Brain Development: The Adolescent Brain. *Neuroimage, 61,* 397-406. https://doi.org/10.1016/j.neuroimage.2011.11.080

Butcher, K. R., & Sumner, T. (2011). Self-Directed Learning and the Sensemaking Paradox. *Human-Computer Interaction, 26,* 123-159. https://doi.org/10.1080/07370024.2011.556552

Cowan, N. (2014). Working Memory Underpins Cognitive Development, Learning, and Education. *Educational Psychology Review, 26,* 197-223. https://doi.org/10.1007/s10648-013-9246-y

Cragg, L., & Gilmore, C. (2014). Trends in Neuroscience and Education. *Trends in Neuroscience and Education, 3,* 63-68. https://doi.org/10.1016/j.tine.2013.12.001

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of Cognitive Control and Executive Functions from 4 to 13 Years: Evidence from Manipulations of Memory, Inhibition, and Task Switching. *Neuropsychologia, 44,* 2037-2078. https://doi.org/10.1016/j.neuropsychologia.2006.02.006

De Bruin, A. B., & van Merriënboer, J. J. (2017). Bridging Cognitive Load and Self-Regulated Learning Research: A Complementary Approach to Contemporary Issues in Educational Research. *Learning and Instruction, 51,* 1-9. https://doi.org/10.1016/j.learninstruc.2017.06.001

De Leeuw, J. R. (2015). jsPsych: A JavaScript Library for Creating Behavioral Experiments in a Web Browser. *Behavior Research Methods, 47,* 1-12. https://doi.org/10.3758/s13428-014-0458-y

Delevich, K., Thomas, A. W., & Wilbrecht, L. (2018). Adolescence and "Late Blooming" Synapses of the Prefrontal Cortex. *Cold Spring Harbor Symposia on Quantitative Biology, 83,* 37-43. https://doi.org/10.1101/sqb.2018.83.037507

Dörrenbächer, L., & Perels, F. (2016). More Is More? Evaluation of Interventions to Foster Self-Regulated Learning in College. *International Journal of Educational Research, 78,* 50-65. https://doi.org/10.1016/j.ijer.2016.05.010

Du Toit-Brits, C. (2018). Towards a Transformative and Holistic Continuing Self-Directed Learning Theory. *South African Journal of Higher Education, 32,* 51-65. https://doi.org/10.20853/32-4-2434

Duit, R., Treagust, D., & Widodo, A. (2008). Teaching Science for Conceptual Change: Theory and Practice. In *International Handbook of Research on Conceptual Change* (pp. 629-646). Routledge.

Engle, R. W. (2018). Working Memory and Executive Attention: A Revisit. *Perspectives on Psychological Science, 13,* 190-193. https://doi.org/10.1177/1745691617720478

Faize, F. A., Husain, W., & Nisar, F. (2017). A Critical Review of Scientific Argumentation in Science Education. *Eurasia Journal of Mathematics, Science and Technology Education, 14,* 475-483. https://doi.org/10.12973/ejmste/80353

Francom, G. M. (2010). Teach Me How to Learn: Principles for Fostering Students' Self-Directed Learning Skills. *International Journal of Self-Directed Learning, 7,* 29-44.

Gredler, M. E. (2012). Understanding Vygotsky for the Classroom: Is It Too Late? *Educational Psychology Review, 24,* 113-131. https://doi.org/10.1007/s10648-011-9183-6

Hadwin, A., & Oshige, M. (2011). Self-Regulation, Coregulation, and Socially Shared Regulation: Exploring Perspectives of Social in Self-Regulated Learning Theory. *Teachers College Record, 113,* 240-264. https://doi.org/10.1177/016146811111300204

Heddy, B. C., Danielson, R. W., Sinatra, G. M., & Graham, J. (2017). Modifying Knowledge, Emotions, and Attitudes Regarding Genetically Modified Foods. *The Journal of Experimental Education, 85,* 513-533. https://doi.org/10.1080/00220973.2016.1260523

Heflin, H., Shewmaker, J., & Nguyen, J. (2017). Impact of Mobile Technology on Student Attitudes, Engagement, and Learning. *Computers & Education, 107,* 91-99. https://doi.org/10.1016/j.compedu.2017.01.006

Janssen, J., Kirschner, F., Erkens, G., Kirschner, P. A., & Paas, F. (2010). Making the Black Box of Collaborative Learning Transparent: Combining Process-Oriented and Cognitive Load Approaches. *Educational Psychology Review, 22,* 139-154. https://doi.org/10.1007/s10648-010-9131-x

Kirschner, P. A., Sweller, J., & Clark, R. E. (2006). Why Minimal Guidance during Instruction Does Not Work: An Analysis of the Failure of Constructivist, Discovery, Problem-Based, Experiential, and Inquiry-Based Teaching. *Educational Psychologist, 41,* 75-86. https://doi.org/10.1207/s15326985ep4102_1

Lee, K., Bull, R., & Ho, R. M. (2013). Developmental Changes in Executive Functioning. *Child Development, 84,* 1933-1953. https://doi.org/10.1111/cdev.12096

Lee, K., Tsai, P.-S., Chai, C., & Koh, J. (2014). Students' Perceptions of Self-Directed Learning and Collaborative Learning with and without Technology. *Journal of Computer Assisted Learning, 30,* 425-437. https://doi.org/10.1111/jcal.12055

Liu, O. L. (2009). An Investigation of Factors Affecting Gender Differences in Standardized Math Performance: Results from US and Hong Kong 15 Year Olds. *International Journal of Testing, 9,* 215-237. https://doi.org/10.1080/15305050903106875

Meixner, J. M., Warner, G. J., Lensing, N., Schiefele, U., & Elsner, B. (2019). The Relation between Executive Functions and Reading Comprehension in Primary-School Students: A Cross-Lagged-Panel Analysis. *Early Childhood Research Quarterly, 46,* 62-74. https://doi.org/10.1016/j.ecresq.2018.04.010

Nęcka, E., & Lulewicz, A. (2016). Capacity, Control, or Both—Which Aspects of Working Memory Contribute to Children's General Fluid Intelligence? *Polish Psychological Bulletin, 47,* 21-28. https://doi.org/10.1515/ppb-2016-0003

OECD-PISA (1999). *Measuring Student Knowledge and Skills: A New Framework for Assessment*. OECD.

Paas, F., & Sweller, J. (2012). An Evolutionary Upgrade of Cognitive Load Theory: Using the Human Motor System and Collaboration to Support the Learning of Complex Cognitive Tasks. *Educational Psychology Review, 24,* 27-45. https://doi.org/10.1007/s10648-011-9179-2

Reio, T. G., & Davis, W. (2005). Age and Gender Differences in Self-Directed Learning Readiness: A Developmental Perspective. *International Journal of Self-Directed Learning, 2,* 40-49.

Roebers, C. M. (2017). Executive Function and Metacognition: Towards a Unifying Framework of Cognitive Self-Regulation. *Developmental Review, 45,* 31-51. https://doi.org/10.1016/j.dr.2017.04.001

Roger, T., & Johnson, D. W. (1994). An Overview of Cooperative Learning. In J. Thousand, A. Villa, & A. Nevin (Eds.), *Creativity and Collaborative Learning* (pp. 1-21). Paul H. Brookes Publishing.

Rutherford, T., Buschkuehl, M., Jaeggi, S. M., & Farkas, G. (2018). Links between Achievement, Executive Functions, and Self-Regulated Learning. *Applied Cognitive Psychology, 32,* 763-774. https://doi.org/10.1002/acp.3462

Schwaighofer, M., Bühner, M., & Fischer, F. (2017). Executive Functions in the Context of Complex Learning: Malleable Moderators? *Frontline Learning Research, 5,* 58-75.

https://doi.org/10.14786/flr.v5i1.268

Schweder, S., & Raufelder, D. (2019). Positive Emotions, Learning Behavior and Teacher Support in Self-Directed Learning during Adolescence: Do Age and Gender Matter? *Journal of Adolescence, 73,* 73-84. https://doi.org/10.1016/j.adolescence.2019.04.004

Schweder, S., & Raufelder, D. (2021). Needs Satisfaction and Motivation among Adolescent Boys and Girls during Self-Directed Learning Intervention. *Journal of Adolescence, 88,* 1-13. https://doi.org/10.1016/j.adolescence.2021.01.007

Shipstead, Z., Harrison, T. L., & Engle, R. W. (2015). Working Memory Capacity and the Scope and Control of Attention. *Attention, Perception, & Psychophysics, 77,* 1863-1880. https://doi.org/10.3758/s13414-015-0899-0

Stöckert, A., & Bogner, F. X. (2020). Cognitive Learning about Waste Management: How Relevance and Interest Influence Long-Term Knowledge. *Education Sciences, 10,* 102. https://doi.org/10.3390/educsci10040102

Sweller, J., van Merriënboer, J. J., & Paas, F. (2019). Cognitive Architecture and Instructional Design: 20 Years Later. *Educational Psychology Review, 31,* 261-292. https://doi.org/10.1007/s10648-019-09465-5

Uytun, M. C. (2018). Development Period of Prefrontal Cortex. In *Prefrontal Cortex* (pp. 3-22). IntechOpen. https://doi.org/10.5772/intechopen.78697

Vygotsky, L. S. (1994). The Development of Academic Concepts in School Aged Children. *The Vygotsky Reader, 355,* 370.

Weber, V. M. R., Fernandes, D. Z., Volpato, L. A., de Oliveira Bueno, M. R., Romanzini, M., Castro-Piñero, J. et al. (2021). Development of Cardiorespiratory Fitness Standards for Working Memory Using Receiver Operating Curves in 15-Year-Old Adolescents. *BMC Pediatrics, 21,* Article No. 208. https://doi.org/10.1186/s12887-021-02681-5

Young, J. Q., Van Merrienboer, J., Durning, S., & Ten Cate, O. (2014). Cognitive Load Theory: Implications for Medical Education: AMEE Guide No. 86. *Medical Teacher, 36,* 371-384. https://doi.org/10.3109/0142159X.2014.889290

Zepeda, C. D., Richey, J. E., Ronevich, P., & Nokes-Malach, T. J. (2015). Direct Instruction of Metacognition Benefits Adolescent Science Learning, Transfer, and Motivation: An *in Vivo* Study. *Journal of Educational Psychology, 107,* 954. https://doi.org/10.1037/edu0000022