Article

Fostering Self-Directed Learning in Mathematics Education: Empowering Learners Through Technology-Supported Cooperative Learning

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Abstract

In the current knowledge- and information-driven era, learners should develop self-directed learning (SDL) abilities at the classroom level. This study focused on the use of technology-supported cooperative learning (TSCL) to improve grade 8 mathematics learners' SDL abilities. A mixed-methods methodology with a sequential explanatory design was adopted. This study used a design-based research approach (DBR) with two iterations. In the study's first iterative intervention cycle, 427 grade 8 mathematics learners from 10 secondary schools in Rustenburg were purposively selected, and in the second iteration of the study, 522 grade 8 mathematics learners were enrolled. Data collection included quantitative assessment using the Self-Directed Learning Instrument (SDLI) and qualitative methods such as classroom observations, semi-structured interviews, and reflective journals. Data analysis involved descriptive statistics for quantitative data and thematic coding for qualitative data. The study found that the TSCL intervention improved the participants' SDL abilities. The implementation of TSCL in the classroom provided an atmosphere in which learners could connect with their peers as a source of knowledge, improve communication and social skills, learn how to find relevant resources, and take ownership of their own learning process. The research findings contribute to the body of knowledge on cooperative learning (CL) as a learning approach for promoting SDL.

Keywords: mathematics education; cooperative learning; self-directed learning; technology-supported cooperative learning

UNISA university of south africa PRESS

International Journal of Educational Development in Africa
Volume 10 | Sup | 2025 | #17346 | 21 pages

https://doi.org/10.25159/2312-3540/17346
ISSN 2312-3540 (Online), ISSN 2312-3540 (Print)

Introduction and Problem Statement

Mathematics education in South Africa has been a topic of concern for many years because of learners' poor performance (Jojo 2019; Mabena et al. 2021), which is considered to be among the worst in the world (Von Davier et al. 2024). Efforts have been made by educationists to improve the quality of mathematics education and learners' performance (Maaga 2017; Spaull 2019). Apart from a decline in the number of learners who write the grade 12 mathematics exam, the drop in the pass rate of grade 12 mathematics learners is a great concern (Department of Basic Education 2024). In addition, the results of the Trends in International Mathematics and Science Study (TIMSS) clearly show that South African learners' performance is far below the international average (Mullis et al. 2020). This creates a serious concern in terms of mathematical knowledge and skills as well as learners gaining access to higher education.

The World Economic Forum (2018), the National Youth Policy (Republic of South Africa, 2020), and other studies (e.g., Fitria et al. 2023; Nieswandt 2017) suggest that South African learners lack the critical skills necessary for success in the twenty-first century, including critical thinking, creativity, collaboration, communication, problem-solving, technology literacy, leadership, flexibility, adaptability, and innovation. Equipping learners with these skills could help them become lifelong learners, which is essential for self-directed learning (SDL) (Du Toit 2019). SDL is "a process in which individuals take the initiative, with or without the help of others, in diagnosing their learning needs, formulating learning goals, identifying human and material resources for learning, choosing and implementing appropriate learning strategies, and evaluating learning outcomes" (Knowles 1975, 18). Twenty-first century skills and SDL skills are essential agents to empower learners in a society in which mathematics and mathematical achievement are highly rated (Bosch et al. 2019; Pokhrel et al. 2024). Learners who are self-directed can carry out different learning strategies, think deeply about issues, communicate, and work cooperatively as a team, leading to enhanced success (Tang 2024).

The extent to which technology-supported cooperative learning (TSCL) can be used to promote SDL in mathematics education in South Africa has not been adequately explored. This article reports on the use of TSCL as a viable option for enhancing grade 8 mathematics learners' SDL ability through discussions and interaction with one another in a cooperative environment. Cooperative learning (CL) has been shown to be an effective teaching strategy that provides learners with opportunities to learn from one another (Johnson and Johnson 2014), and the use of technology in education is recognised as an approach to prepare learners for the twenty-first century (Holt and Payne 2020). Technology widens learners' access to new opportunities for learning, critical thinking, and collaboration skills, and it improves educational competencies, making it a significant means to address educational shortcomings in the developing world (Johnson and Johnson 2014).

Literature Review

Numerous studies have focused on elucidating the underlying causes of poor learner performance in mathematics (Graven and Venkat 2017; Pournara et al. 2016; Spaull 2019). These studies attribute the subpar mathematics results primarily to factors associated with both teachers and learners. Graven and Venkat (2017) identified insufficient teacher content knowledge, outdated pedagogical methods, overcrowded classrooms, and teacher absenteeism as contributors to inadequate learner performance. Pournara et al. (2016) highlighted additional factors such as curriculum changes, insufficient resources, and the prevalent anxiety about and fear of mathematics among students. Furthermore, learner-related challenges like poor foundational mathematical skills, low levels of self-directed learning, low motivation, language hurdles, and socio-economic challenges add to weak performance (Spaull 2019). International assessments such as TIMSS and the Programme for International Student Assessment (PISA) consistently rank South Africa below global averages, underscoring a significant performance disparity with other nations (Mullis et al. 2020).

The consequences of poor performance in mathematics are far-reaching, as the number of learners who are adequately prepared for careers in the science, technology, engineering, and mathematics (STEM) fields is reduced (Maaga 2017). This performance drop is primarily because of the belief that mathematics is a tough subject and because students lack confidence and motivation (Spaull 2019). A critical challenge facing mathematics education in South Africa is the persistent reliance on traditional teaching methodologies, which often prioritise rote memorisation and passive learning (Mosiane 2020). These methods hinder the development of crucial skills such as critical thinking and problem-solving, essential for mathematical proficiency (Mahlaba 2020). The prevalence of traditional teaching strategies, known for their monotony and lack of inspiration, contributes to learner disengagement (Taylor 2018). Traditional teaching approaches frequently fall short in addressing the diverse learning needs of South African learners. As such, these results underscore the urgent need for a thorough investigation of the factors contributing to the country's poor mathematical performance.

In response to the challenges facing mathematics education in South Africa, there is a growing body of literature advocating for the incorporation of innovative teaching methodologies (Dahal et al. 2020; Naidu 2021). TSCL has emerged as a promising strategy that can empower learners to cultivate SDL skills. The concepts of SDL, CL, and TSCL are not mutually exclusive but rather complementary. The integration of TSCL into mathematics education aligns with the five essential elements of CL outlined by Johnson and Johnson (2013), namely positive interdependence, individual accountability, promotive interaction, appropriate use of social skills, and group processing, which collectively contribute to the collaborative and supportive learning environment advocated by CL. Self-directed learners can benefit from CL experiences, as working with peers exposes them to diverse perspectives and stimulates critical thinking (Bosch et al. 2019; Lubbe 2015; Petersen and Mentz 2016). Integrating technology into CL further enhances the potential for collaboration and resource sharing, especially in asynchronous and online environments (Sekano et al. 2023). Moreover, it facilitates enhanced communication and teamwork, fostering an environment where learners can actively participate and contribute to the collective learning experience (Johnson and Johnson 2019). In contrast, scholars contend that CL can provide the social support and motivation that some self-directed learners may lack when studying in isolation (Bosch et al. 2019). This shift from traditional teaching methods to collaborative, technology-enhanced approaches aligns with the evolving needs of contemporary education (Dahal et al. 2020; Naidu 2021).

The cultivation of SDL through TSCL has far-reaching implications for academic success (Sekano et al. 2023). Research indicates that when learners take ownership of their learning process, they are more likely to engage in various learning strategies, engage deeply in academic content, and develop critical thinking skills (Knowles 1975). Garrison (1997) argued that learners who engage in SDL activities demonstrate higher levels of motivation, achievement, and overall academic success, a view that is supported by van Zyl and Mentz (2022). As learners become more adept at managing their own learning, they are better equipped to navigate complex issues, collaborate effectively in group settings, and utilise diverse learning strategies (Boyer et al. 2014). This holistic approach to education aligns with the goals of STEM fields, where problem-solving and collaboration are essential skills. Therefore, the integration of TSCL into mathematics education in South Africa holds the potential to address not only the immediate challenges related to poor performance but also to foster a transformative learning environment conducive to long-term academic success.

Candy's (1991) perspective on SDL provides valuable insights into the variability inherent in learners' ability to direct their own learning experiences. According to Candy, SDL is a multifaceted concept influenced by individual motivations, preferences, and the ability to set and achieve learning goals. The South African context, marked by declining interest in mathematics, socio-economic disparities, and traditional teaching methodologies, underscores the importance of understanding how Candy's SDL framework may vary among learners. Candy suggests that learners with a strong intrinsic motivation for learning may exhibit more robust SDL skills, whereas those lacking motivation may struggle to engage in self-directed activities. As such, interventions like TSCL should consider these individual differences in SDL propensity to tailor strategies effectively.

Building on Candy's (1991) conceptualisation of SDL, the development of specific skills is paramount for learners to become self-directed. Skills such as critical thinking, problem-solving, and effective communication align with the attributes associated with successful SDL (Gibbons 2002). In the South African context, where learners face challenges in mathematics education, interventions like TSCL should aim not only to instil these skills but also to assess and nurture them continuously (Sekano et al. 2023).

By doing so, TSCL becomes a mechanism for developing the skills that are crucial for overcoming the obstacles posed by traditional teaching methodologies and facilitating the self-directedness needed for academic success.

The characteristics of SDL involve learners' capacity to take the initiative, set goals, and monitor their learning progress independently. Guglielmino (2013) emphasises that self-directed learners actively engage with the learning process, demonstrating autonomy and a proactive approach. In the context of mathematics education, the prevalent traditional teaching methodologies, characterised by rote memorisation and passive learning, hinder the development of these crucial SDL characteristics. Consequently, interventions such as TSCL should address these impediments by fostering an environment that encourages goal-setting, initiative, and independent thinking among learners.

Methodology

We employed a mixed methods research design, combining both quantitative and qualitative approaches to enhance the comprehensiveness and accuracy of our findings (Creswell and Creswell 2023). The research paradigm guiding our work is rooted in pragmatism, allowing flexibility in employing various methods and accommodating different world-views (Plano Clark and Ivankova 2024). This choice aligns with the study's focus on grade 8 mathematics learners' experiences with a TSCL environment. The research design, drawing from Creswell and Plano Clark (2018), involved a design-based research (DBR) approach characterised by iterative cycles of design, implementation, analysis, and revision.

Sample

Because this study followed a DBR approach with two iterations to strengthen the findings, two samples were drawn. For the first iteration, a purposive sample (n1) of 427 grade 8 mathematics learners from the 10 secondary schools in Rustenburg, one of the nine education provinces of South Africa, was selected. In the second iterative of the DBR cycle, a sample (n2) of 522 learners was chosen to participate. The second iterative intervention cycle aimed to validate and extend the findings from the first cycle by implementing the TSCL intervention with a new cohort of grade 8 mathematics learners. In each iteration, two schools were purposively selected as the experimental group (EG), while eight other schools served as the control group (CG). The schools are unique since they are the only ones in the area that have implemented paperless teaching and learning practices, where each learner uses their own tablet device for all mathematics lessons, replacing traditional textbooks, homework submissions, and grade reports. By using purposive sampling, the authors selected learners who had direct experience with TSCL within those particular classroom settings. This sampling technique allowed for the selection of participants who possessed insights into the benefits, challenges, and opportunities associated with TSCL in a technology-rich learning environment.

The TSCL Intervention

The TSCL intervention was structured around the five elements of collaborative learning (CL) and integrated multimedia components such as video streaming, instant messaging, video calling, interactive websites, and real-time chat sessions. The tasks designed for this intervention aimed to develop grade 8 mathematics learners' SDL skills including goal setting, self-monitoring, decision-making, problem-solving, independent learning, and collaboration. Activities such as creating a mathematics game using Kahoot, producing a video using a PowerPoint presentation, and engaging in collaborative work on Google Docs were included to encourage critical thinking, independent decision-making, and teamwork. Central to the TSCL intervention was the implementation of the Student Team Achievement Division (STAD) strategy, which is a CL approach that leverages the use of various technological tools to enhance content accessibility. STAD facilitates small group collaboration among learners of differing abilities, enabling them to support one another in grasping the subject matter, interpreting concepts, and discussing solutions to problems and activities assigned by teachers (Tiantong and Teemuangsai 2013).

During this intervention, learners with diverse academic abilities, comprising seven males and five females, from various ethnic backgrounds, participated in the CL experience. The group activities were structured as follows: (a) the facilitator presented the exercise to be tackled; (b) group members had an opportunity to learn together; (c) individual members worked on their assigned tasks; (d) individual quiz scores were added up for each group; and (e) groups that met or exceeded the set performance criteria were rewarded. Additionally, learners were encouraged to compete against themselves rather than against others, creating a more positive and nurturing learning environment that prioritises growth, collaboration, and individual progress. The facilitator's methods and resources aimed to ensure that each group member contributed to the achievement of the group in their own distinct and relevant way, maintaining the structure and coherence of the group. The multimedia features such as photos, video calling, chat rooms, audio files, and voice notes within the STAD strategy provided learners with flexible opportunities to reinforce and improve their SDL abilities while engaging with their peers in a cooperative setting.

Data Collection

The data generated by the intervention consisted of both quantitative and qualitative components. Data collection followed a sequential explanatory mixed methods approach, starting with quantitative data collection through the distribution of the Self-Directed Learning Instrument (SDLI) to participating schools. The SDLI, a validated 20-item questionnaire known for its reliability and validity, was used to assess learners' SDL abilities across four domains: learning motivation, planning and implementation, self-monitoring, and interpersonal communication. In the first iteration, 404 grade 8 mathematics learners out of the total sample of 427 completed the distributed pre-test SDLI questionnaires. A total of 404 questionnaires were distributed during the post-test phase of which 369 were completed. During the second iteration, 522 SDLI pre-test questionnaires were distributed and 513 were completed. A further 513 questionnaires were distributed during the post-test phase, and 454 were completed. The SDLI was administered as a pre-test to establish baseline SDL levels for both the experimental and control groups. After completing the TSCL intervention, the same questionnaire was administered again to measure any changes in SDL abilities.

For qualitative data, the researchers observed learners from the EG during TSCL activities, focusing on collaboration, problem-solving, engagement, and SDL behaviours. Qualitative data gathered through classroom observations, semi-structured interviews, and reflective journals, provided deeper insights into participants' experiences with the TSCL environment. In the first iteration, 17 learners took part in the semi-structured interviews, and 11 learners in the second iteration of the study. To validate the study's findings, a second iterative intervention cycle was conducted, adhering to the design-based approach. This cycle followed a similar design with a new cohort of grade 8 mathematics learners, utilising the same intervention activities and TSCL strategy as in the first cycle.

Data Analysis

Both quantitative and qualitative data underwent rigorous analysis to address the research questions. Descriptive statistical techniques were applied to the quantitative data; the mean values of the domains of the SDLI questionnaire were calculated. The mean is a measure of central tendency that indicates where the data appears to be clustered (Livingston 2004, 117). The SDLI is a self-rating instrument with 20 items split throughout four domains associated with learners' self-directed abilities: learning motivation (items 1–6), planning and implementation (items 7–12), self-monitoring (items 13–16), and interpersonal communication (items 17–20) (Cheng et al. 2010, 1153). The SDLI was rated on a five-point Likert-type scale (1 = strongly disagree, 2 = disagree, 3 = neutral, 4 = agree, and 5 = strongly agree) with a total score ranging between 20 and 100. Cronbach's alpha coefficient was used to ensure reliability in the study. Other studies have found similar results, with Cronbach's alpha coefficients ranging from 0.80 to 0.92 (Cheng et al. 2010; Shen et al. 2014).

Qualitative data analysis involved a thorough examination of transcribed interviews and observational data, employing coding methods to identify patterns and categories. The coding of qualitative data involved an iterative process using ATLAS.ti (version 21), incorporating open coding, axial coding, and selective coding. Data collection ceased upon reaching saturation, ensuring a comprehensive understanding of emerging themes.

Ethical clearance was obtained from the relevant authorities and consent forms were given to participants, with the assurance of anonymity and privacy protection. As required by the institution's Research Ethics Committee, an independent person was involved in gaining consent from the participants.

Results

The results are organised into two parts, with the first part presenting the descriptive statistics of the overall data set, followed by the qualitative results.

Quantitative Results

The SDLI was used to evaluate four domains of self-directed learning: learning motivation, planning and implementation, self-monitoring, and interpersonal communication. Figure 1 presents a summary of the mean values for the experimental and control groups during the first iterative intervention cycle prior to the commencement of the intervention.

Figure 1 illustrates that the CG rated themselves highly across all domains of the SDLI before the intervention commenced. Notably, the learning motivation domain for the CG exhibited the highest mean score among all domains prior to the intervention in the first iterative cycle. The observed differences in learning motivation between the EG and the CG before the intervention may be attributed to various factors, such as prior exposure to technology, differences in teaching styles, classroom environment, socio-economic background, and varying levels of mathematics confidence or anxiety, which are discussed in detail in the discussion section below.

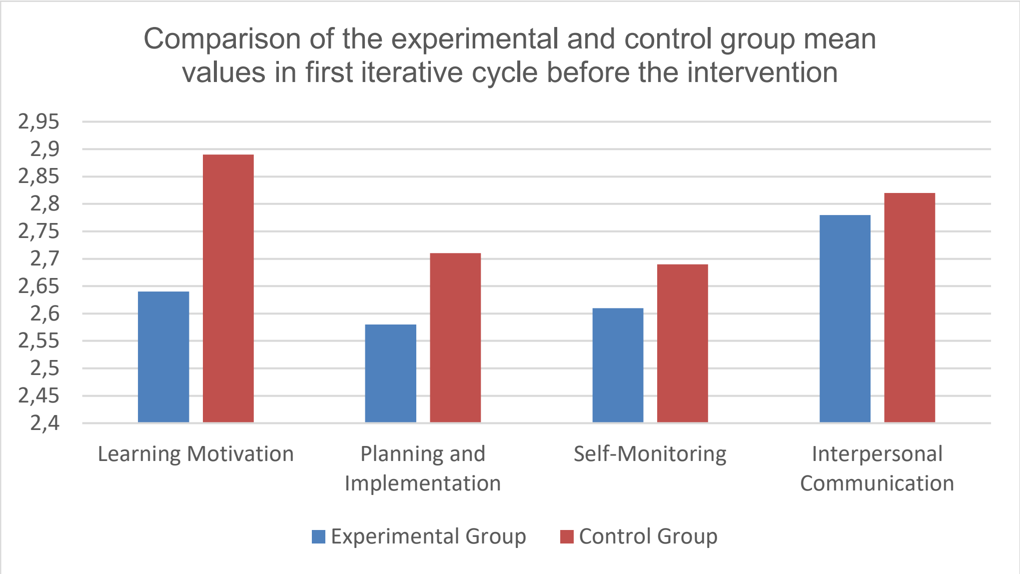

Figure 1: Comparison of the experimental and control group mean values of the SDLI domains in the first iterative intervention cycle before the intervention. Source: Author's compilation

Figure 2 reveals that the CG maintained high self-assessment scores across most domains of the SDLI even after the intervention. Similarly, the EG also reported high scores in most SDLI domains post-intervention. Notably, the domains of learning motivation, planning and implementation, and interpersonal communication exhibited the highest mean scores for the EG after the intervention. To validate these findings, a second iterative intervention cycle was conducted, adhering to the design-based approach. This cycle followed a similar design with a new cohort of grade 8 mathematics learners, using the same intervention activities and TSCL strategy as in the first cycle.

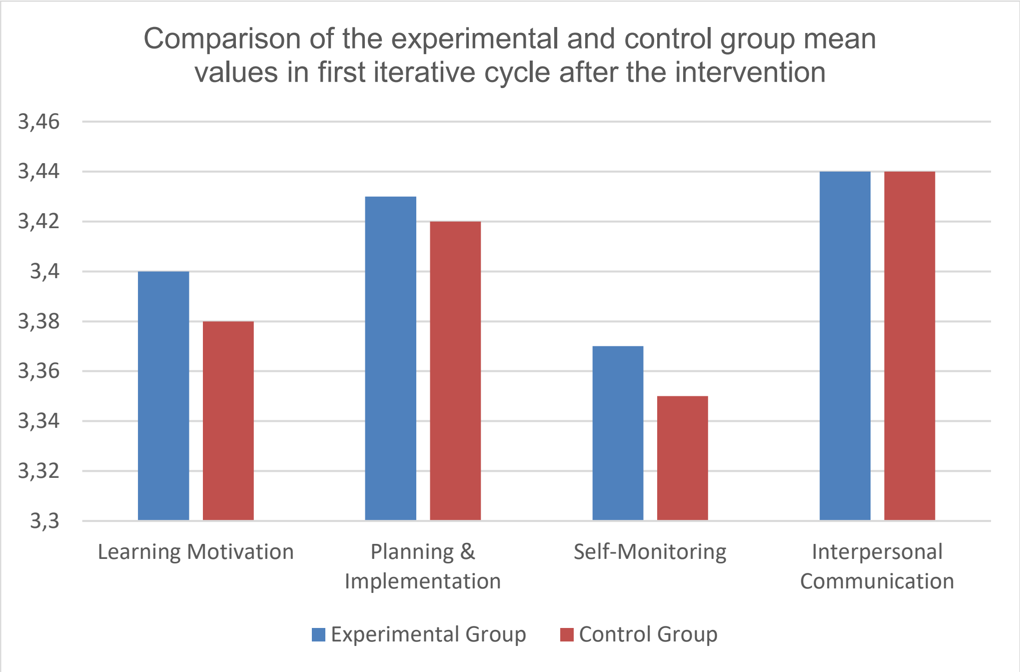

Figure 2: Comparison of the experimental and control group mean values of the SDLI domains in the first iterative intervention cycle after the intervention. Source: Author's own compilation

Figure 3 shows that the CG in the second iterative cycle before the intervention scored themselves high, similar to the scores observed in the first iterative cycle,. In contrast, the EG scored themselves low in all SDLI domains of their SDL ability before the intervention began. This could mean that the EG may not have had the same level of knowledge or skills for learning on their own. Consequently, there is a need for targeted help to improve the SDL abilities of the EG learners. The results suggest a potential deficit in SDL skills among EG learners pre-intervention. This indicates that having explicit teaching strategies (e.g., structured guidance, scaffolding, and TSCL) for developing SDL skills would be beneficial. Teachers should introduce interventions early so they can develop SDL skills and improve their academic performance by taking control of the learning process.

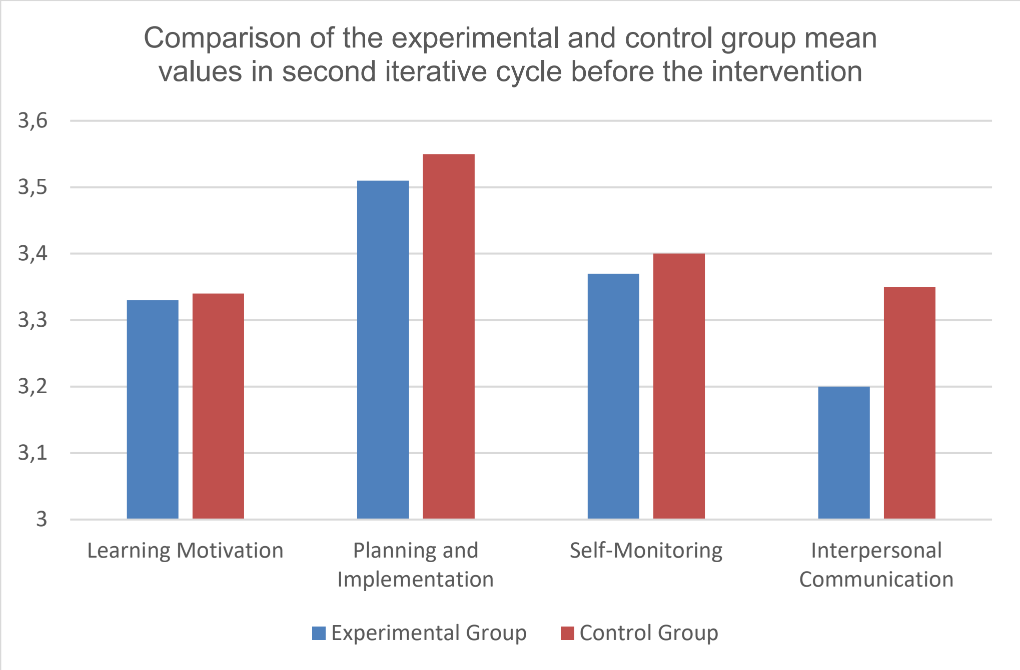

Figure 3: Comparison of the mean values of the SDLI domains in the second iterative intervention cycle between the experimental and control groups before the intervention. Source: Author's own compilation

Figure 4 indicates that the CG again scored their SDL ability high in most SDLI domains after the intervention, except for the planning and implementation domain. Even though the CG did not receive the intervention, they continued to score themselves high in most of the SDLI domains. The EG scored themselves low before the intervention, and their SDLI scores increased after the intervention, mirroring the pattern observed in the first iterative cycle.

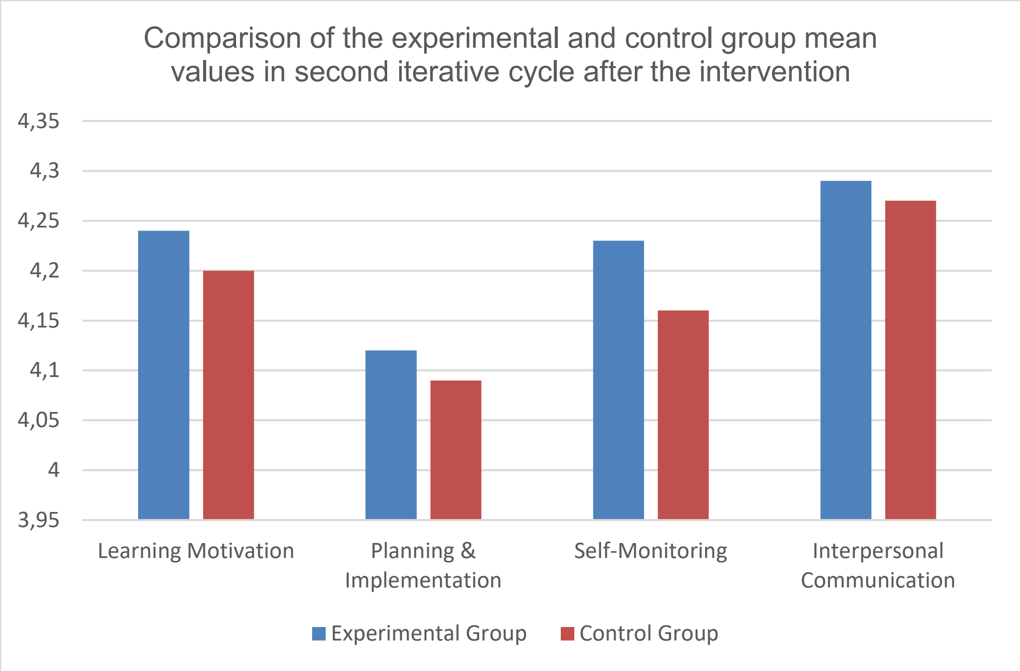

Figure 4: Comparison of the mean values of the SDLI domains in the second iterative intervention cycle between the experimental and control group after the intervention. Source: Author's own compilation

To summarise, the quantitative results have shown that the mean scores for most SDL domains, namely the learning motivation domain, the planning and implementing domain, and the interpersonal communication domain, showed a statistically significant increase, with a moderate practical significance increase in both iterative intervention cycles. The current study's SDLI domains showed Cronbach alpha values of 0.85, 0.79, 0.82, and 0.79, respectively, and an overall Cronbach's alpha coefficient of 0.81. The qualitative results discussed below are also important in understanding how the implementation of TSCL influenced the participants' SDL abilities.

Qualitative Results

The second part presents the qualitative results based on semi-structured interviews with learners. Two key themes, that is, characteristics of SDL and SDL skills, were identified, and data from the participants' responses and the literature review were used to address the research questions. The relationship between themes was determined to develop patterns, and examples from the interviews were cited. The transcriptions were not changed, and names were omitted for confidentiality. There were three identifiers included: the learner (L), the learner identification number, and the quotation number.

Evidence of Self-Directed Learning Characteristics During the Technology-Supported Cooperative Learning Intervention

The primary characteristics of SDL observed during the TSCL intervention sessions include setting clear goals, monitoring and evaluating one's learning process, exhibiting a strong capacity for independent learning, finding joy in the learning process, and effectively organising and planning. The following quotes from learners' interview responses illustrate these points:

> Maths is not my favourite subject... ehm, but the activities we did whenever you are at school ... for me, Sir ... they were more like ... engaging and I enjoyed them. (L1:11)

Other participants highlighted their organisational skills and strategic planning within their small groups. For instance, Participant 6 noted:

> Me and my team were very organised. We made sure that we set an appointment for a catch-up to make sure that everything was ready before submission. (L6:10)

Another participant added:

> Every morning before the screening, we update each other on our progress and then we quickly plan how we are going to do the task going forward. (L5:13)

Many participants also demonstrated an understanding of how to monitor and evaluate their own learning processes. This is exemplified by the following response:

> I think we have to try more at improving to work together as a team because ... ehm ... this thing of having members doing the work on their own ... is not working. (L9:8)

The learners' ability to learn independently was evident from their interview responses, as illustrated by the following comments:

> When I was doing my section of work neh … I tried to visit many different websites. (L6:9)

> I am proud of the amount of information I provided, even when I find the task difficult. (L4:14)

The preceding comments reveal that the participants exhibited a clear grasp of the essential self-directed learning characteristics. This understanding is further corroborated by entries in the reflective journal which document the participants' proactive approach:

> The initial reaction of learners when assigned a new task was that they did not want to wait for me (the researcher) to teach them how to do it. They were eager to undertake the tasks independently and complete them on time. (Researcher reflective journal, 17 November 2021)

The qualitative findings on the characteristics of SDL shed valuable light on the nuanced and multifaceted nature of learners' autonomous engagement in the educational process.

Evidence of Self-Directed Learning Skills During the Technology-Supported Cooperative Learning Intervention

SDL skills, including decision-making, taking responsibility for one's own learning, goal setting, and perceiving change as a challenge rather than an obstacle, were prominently displayed during the TSCL intervention sessions. This is evident from the participants' responses. For example, Participant 15 and Participant 4 detailed their decision-making processes during group tasks:

> Making critical decisions such as paying close attention to the prescribed rules and following the instructions on each task helped us to avoid many mistakes. (P15:18)

> It is important to consider how my actions in the group affect my learning, as well as the learning experiences of others. (P4:15)

Another participant shared their perspective on finding relevant information:

> We were not told to copy definitions from the board … uhm … we had to find them from dictionaries, the Internet, and this was nice because we could see pictures or go to YouTube to watch videos of someone explaining that thing. (P9:16)

Other participants also articulated how they took responsibility for their own learning:

> In our group, we meet every after school to catch up on our group work. (L12:18)

> What helped us in our group to succeed is that we always divided tasks according to our strengths. For example, you see, I am a fast typer neh ... so I was a scriber. (L11:17)

It also seemed clear that participants were able to set their own goals. P2 said:

> ... ehm … I am willing to obtain a distinction by the end of this year. (P2:13)

Another participant shared their perspective:

> You see, *mina* [me] ... (long pause) ... I am an "A" student. Maths has always been my strength since grade 1, and I am determined to maintain that. (P11:10)

However, some participants encountered difficulties in their mathematics learning, as indicated by several of their responses:

> This maths is difficult for me. .... it, it has a lot of alphabets ... I mean letters … and it is so confusing. (L3:8)

> I used to get 70 plus in primary school neh … but now, Sir, even just to get 50% is a struggle. (L13:14)

> Every day, we are always finding x … and there are different methods for every question. (L2:11)

> Eish … you transpose neh, then the teacher says that you were supposed to divide, when you divide, she will be like, you were supposed to multiply. *Mina* [me] ... I don't know. (L11:13)

These learners, however, learned to overcome obstacles and developed effective problem-solving skills. Participants expressed how they perceive problems as challenges rather than obstacles, as evidenced by their sentiments:

> What I have noticed is that I have to read the problem neh … then, I always make sure that I understand all the words and hints before solving the problem. (L11:19)

> You may need to read the problem two or more times. If there are words you don't understand, look them up in a dictionary or on the Internet. (L13:17)

> You can use any letter for the variable, but it may help you to choose one that helps you remember what it represents. (L2:21)

> Even if you know the answer right away, using algebra will better prepare you to solve problems that do not have obvious answers. (L3:18)

The qualitative results underscore the tangible evidence of SDL skills demonstrated by participants within the context of the TSCL intervention, offering valuable insights into the dynamic interplay between technology integration and the cultivation of autonomous learning capabilities.

Discussion of Qualitative and Quantitative Results

The study used both quantitative and qualitative research methods to gather data. The findings of the first iterative intervention cycle showed that the TSCL intervention had a slight impact on the EG. One potential explanation for this is that the EG participants may have possessed a certain degree of SDL, as suggested by Candy (1991). However, the results of the second iterative intervention cycle and the qualitative results showed that the TSCL intervention had a positive effect on the participants' SDL abilities. These findings suggest that the TSCL intervention contributed to the participants' learning motivation, planning and implementation, and self-monitoring domains of SDL. The study's results are consistent with previous research by Petersen and Mentz (2016) and Lubbe (2015) which emphasised the benefits of CL for improving learners' SDL abilities. The present study found similar results in the first iterative intervention cycle, but the second iterative intervention cycle demonstrated the positive effect of TSCL on the participants' SDL abilities.

Many participants found the content of the TSCL intervention sessions to be highly relevant, demonstrating a strong interest and valuing the material they were learning. Reflective journal entries support this, showing that the participants recognised patterns and contextualised new information with prior knowledge. For instance, the participants identified key resources such as "the Internet and team members" as crucial for their learning success (researcher's reflective journal, 20 January 2022). Most participants described their time management strategies, including goal-setting and identifying areas for improvement in future tasks—key characteristics of self-directed learners, as highlighted in the literature review.

The participants' remarks clearly indicate an enhancement in their SDL abilities. During the TSCL sessions, the participants developed various SDL skills, including taking initiative and making informed decisions by devising multiple solutions to achieve their goals. Many reported meeting virtually after school hours as a strategy to complete assigned tasks and reflected on their use of technology to find relevant information. Terms such as "selected," "decided," "strategised," and "executed" exemplify the new SDL skills acquired during the TSCL intervention sessions.

The results further indicated that the participants enjoyed using different apps for learning, recording, editing, and producing their own videos. Technology made learning more exciting and enjoyable, and the widespread use of technology in the participants' daily lives made it very relevant to them. The participants experienced a constructive atmosphere marked by positive energy, a sense of teamwork and trust among themselves, and technology-enabled active participation in the learning process, which allowed them to work at their own pace and adapt their learning to their specific needs and learning styles. Furthermore, technology provided the participants with different experiences compared with their regular mathematics classes, and they found it easier to find information quickly and communicate with each other at any time, from different locations. Specific remarks from participants highlighted how tools like Google Docs, Kahoot, and video streaming facilitated real-time communication and knowledge sharing, enhancing their learning experience compared to traditional mathematics classes. The findings corroborate the literature that supports the notion that technological tools offer diverse and interactive learning environments (Dahal et al. 2020; Naidu 2021).

With regard to the characteristics of SDL identified during the intervention, the participants demonstrated that they could set clear goals, monitor and evaluate their learning process, learn independently, and plan and organise their work, consistent with the attributes associated with self-directed learners (Knowles 1975; Guglielmino 2013). The participants' responses showed that they enjoyed learning and could work well in teams, which is in line with CL literature emphasising the importance of interpersonal skills in cooperative educational settings (Johnson and Johnson 2019). The participants' inclination to enjoy learning and their capacity to view change as a challenge rather than an obstacle resonates with the motivational aspects of SDL highlighted in previous research (Candy 1991). The challenges faced by some participants in mathematics learning, leading to the development of problem-solving skills, further underscores the dynamic nature of SDL and its adaptive response to subject-specific difficulties (Du Toit 2019). In essence, the observed SDL characteristics in our study align with established literature, contributing to the broader understanding of SDL in educational contexts (Bosch et al. 2019; Petersen and Mentz 2016).

The benefits of CL were also evident in that the participants were able to clarify concepts and ideas and receive support from their peers. These observed benefits of CL in the current study resonate with established literature emphasising the positive impact of CL on students' understanding and social interactions (Johnson and Johnson 2019). The effectiveness of a CL environment was evident through the manifestation of the five elements—positive interdependence, individual accountability, promotive interaction, appropriate use of social skills, and group processing—essential for successful CL implementation (Johnson and Johnson 2013). Positive interdependence was visible when the participants worked together in such a manner that each group member depended on other members to complete the task. Individual accountability was visible when participants held each other accountable for contributing to achieving the goal of the group. Promotive interaction, as evidenced by participants encouraging and supporting each other, aligns with the principle that cooperative efforts foster a supportive and affirming learning environment. In essence, the findings corroborate the literature, emphasising the efficacy of CL in promoting collaborative learning environments and the significance of adhering to its fundamental elements for optimal outcomes.

Implications

The study's findings underscore the relevance and impact of technology integration in the learning process. The participants' enjoyment of various learning apps, engagement in producing videos, and the positive experiences derived from TSCL sessions highlight the significance of incorporating technology into educational practices. This implies a need for educational institutions to invest in technology infrastructure and provide training to educators to facilitate the seamless integration of technology, making learning more exciting, enjoyable, and relevant. Furthermore, the study's findings have important implications for teaching and learning practices. Teachers can use TSCL strategies to enhance learners' SDL abilities by encouraging learners to work in groups, share ideas, and develop their social skills. The study's findings also suggest that interventions that benefit a group of learners may have a positive effect on other learners who did not receive the intervention. The positive outcomes also emphasise the potential of technology to foster a positive learning environment, teamwork, trust, and active participation, allowing students to work at their own pace and adapt learning to their specific needs and styles. Therefore, teachers should consider using CL strategies in their teaching practices to benefit a larger group of learners.

The study also highlights the value of using a mixed-methods approach to gain a deeper understanding of the impact of interventions. The study emphasises the need to focus on different SDL domains when designing interventions and to promote self-monitoring of learners' progress, which can be achieved by allowing learners to link newly acquired knowledge to what they have already learned and experienced. Further research is needed to explore the long-term impact of TSCL interventions on learners' SDL abilities and to investigate how the use of different apps and software can provide opportunities for making learning more effective and enjoyable.

Conclusion

The results showed that the intervention did not have a significant effect on the participants' SDL abilities during the first iterative intervention cycle. However, the second iterative intervention cycle and qualitative data indicated that the TSCL intervention contributed to developing the learners' SDL abilities. This indicates that long-lasting exposure to TSCL promotes SDL skills more than short-term intervention. This gradual progression of learners towards employing SDL strategies, evidenced through quantitative data collected from learners' SDLI scores and qualitative learner reflection data, confirms the need for longer-term and comprehensive implementation of TSCL in mathematics education. The observed SDL characteristics align with established literature, contributing substantively to our understanding of SDL in the educational context. As education continues to evolve, the identified benefits of CL, such as positive interdependence and individual accountability, reaffirm the efficacy of CL environments. This study contributes valuable knowledge for educators, policymakers, and researchers aiming to empower learners through innovative pedagogical approaches that leverage technology and CL strategies in fostering SDL skills in mathematics education.

Acknowledgements

This research project was supported by the National Research Foundation (NRF) of South Africa (Grant Number 149119). The grant holder acknowledges that the opinions, findings, conclusions, or recommendations presented in any publication resulting from NRF-supported research are solely those of the author(s) and that the NRF bears no responsibility or liability in this context. This article is based on the first author's PhD dissertation (Sekano 2023).

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