




Exploring the dynamics of self-regulated learning in online courses: trajectories of self-regulated learning and the role of basic psychological needs satisfaction across different achievement levels

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Abstract

This study aimed to investigate the trajectories of students' self-regulated learning in an online course and the predictive role of students' satisfaction with basic psychological needs (autonomy, competence, relatedness) on these trajectories. Additionally, the potential variation in the relationship between basic psychological needs and self-regulated learning based on students' achievement levels was examined. The analysis of data revealed a significant increase in students' self-regulated learning scores throughout the three-month course. Data from 1,105 elementary and middle school students participating in an online learning program were collected over four 12-week periods. This study confirmed the increase in learners' self-regulated learning in an online learning environment over a 12-week period. The study found that autonomy, competence, and relatedness were related to the initial value of self-regulated learning but did not significantly influence the growth of self-regulated learning over the course. The study also found that the relationship between basic psychological needs and self-regulated learning varied among different achievement groups. Autonomy and competence played a significant role in predicting the initial level of self-regulated learning in all groups, regardless of achievement level, whereas relatedness had the most substantial effect for the high-achieving group.

Keywords Online learning environment · Self-regulated learning · Basic psychological needs · Multilevel modeling · Latent growth modeling

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1 Introduction

The recent surge in online learning due to the COVID-19 pandemic has once again emphasized the significance of students' self-regulated learning. Self-regulated learning involves a learner's efforts to systematically manage the learning process to achieve their goals (Zimmerman & Schunk, 2011). Learners with high self-regulation set personal goals and actively participate in learning by using effective strategies (Pintrich & De Groot, 1990; Zimmerman, 1990). Although self-regulated learning is crucial in all learning situations, it is especially important in online education. In online learning environments, where teachers and students are separated by space and time, the responsibility for planning and performing learning lies entirely with the learner (Artino, 2008; Hart, 2012; Lehmann et al., 2014). Thus, the success of online learning depends on how autonomously and actively the student engages in the learning process (You, 2015; Wong et al., 2019). Consistent findings from research indicate that the success of online learning significantly depends on the level of self-regulated learning (Broadbent & Poon, 2015; Wong et al., 2019).

The significant correlation between self-regulated learning and students' success raises interest in understanding how self-regulated learning can be cultivated. There is growing interest in whether online learning environments serve merely as a research background or if they can foster students' self-regulated learning. Researchers argue that online learning environments not only require self-regulated learning but also have the potential to enhance it. Compared to traditional face-to-face classes, online learning environments demand greater control from students over their learning and require them to actively and autonomously engage in the process (Wang et al., 2013). Except for some intervention or quasi-experimental studies (e.g., Jansen et al., 2020), research on the extent to which continuous engagement in online learning environments can develop self-regulated learning in natural settings is limited. In general, knowledge about how students' self-regulated learning evolves over time is limited.

According to self-determination theory, self-regulated learning, which necessitates active and autonomous engagement, can be influenced by the satisfaction of individuals' basic psychological needs—autonomy, competence, and relatedness (Ryan & Deci, 2020). This satisfaction is crucial for fostering self-determined behaviors. Studies have shown that when learners' autonomy, competence, and relatedness needs are met, they are more likely to be intrinsically motivated, engage in deep learning strategies, persist in the face of challenges, and achieve better academic outcomes (Deci et al., 2001; Vallerand et al., 1997; Williams et al., 2004). In the context of online learning, where learners have greater control over their learning process, satisfying these basic psychological needs becomes even more crucial. Online learning environments require learners to be proactive, autonomous, and responsible for their learning (You, 2015; Wong et al., 2019).

The importance of basic psychological needs and self-regulated learning in education has been demonstrated in various studies. However, research exploring the relationship between these two constructs is limited, especially in the

context of online learning environments. For example, in online learning, Wong (2020) reported that students' autonomy and competence were satisfied, Zhou et al. (2021) identified a significant association between relatedness and self-regulated learning, and Bai and Gu (2022) found a meaningful correlation between autonomy and self-regulated learning. Despite these contributions, these studies fall short of comprehensively examining the relationship between all three components of basic psychological needs (autonomy, competence, and relatedness) and self-regulated learning. Additionally, few studies have investigated how the satisfaction of basic psychological needs influences the development of self-regulated learning over time in online settings. For instance, Hidayatullah and Csíkos (2023) explored the relationship between the three basic psychological needs (perceived autonomy, competence, and relatedness) and subcomponents of online self-regulated learning. They found that perceived autonomy predicted goal setting, environmental structuring, time management, and self-evaluation. However, their study did not address these relationships from the perspective of self-regulated learning development over time. Given the growing prevalence of online learning and the increasing importance of self-regulated learning, it is crucial to examine not only the developmental patterns of self-regulated learning in online courses but also how individual psychological characteristics, such as the satisfaction of basic psychological needs, are related to this development.

The benefit of self-regulated learning support has been found to vary depending on students' achievement levels (e.g., Bannert et al., 2014; Dörrenbächer & Perels, 2016; González-Pienda et al., 2014). Additionally, it is theoretically expected that the influence of satisfying basic psychological needs may also differ based on achievement levels. However, there is a lack of empirical research investigating this relationship. To address this gap, we further examined how the relationship between the satisfaction of basic psychological needs and the trajectory of self-regulated learning might differ depending on students' achievement levels. This research aims to enhance our understanding of student engagement and self-regulated learning in online environments and to identify students who may benefit from targeted support in developing their self-regulated learning.

2 Literature review

2.1 Self-regulated learning

2.1.1 Self-regulated learning in online learning contexts

Self-regulated learning refers to the self-directed processes by which learners actively take control of and manage their cognition, motivation, and behavior to achieve their learning goals (Zimmerman, 2000). Self-regulated learning is a proactive process in which learners set goals for learning and adapt to challenges to enhance learning outcomes (Pintrich et al., 2000). Several theoretical models explain self-regulated learning in academic settings (Panadero, 2017), and most of which propose that regulatory processes consist of a multifaceted construct divided into

various sub-components. A notable model of self-regulated learning includes four phases: planning, monitoring, control, and reflection (Pintrich et al., 2000; Schunk, 2005).

In the planning phase, individuals choose strategies and allocate resources to efficiently complete tasks. Self-regulated learners set specific goals, create study schedules, and distribute time across different activities. The monitoring phase involves tracking one's performance, where self-regulated learners stay attentive and query themselves about the material, helping them focus on studying and understanding. In the control phase, learners regulate their cognition, motivation, behavior, and contextual factors in response to their monitoring with the set goals. Finally, during the reflection phase, learners evaluate their performance against their goals or standards to determine the extent of their achievement and identify areas for improvement. In autonomous online environments, where physical separation between teachers and students prevails, students can decide when, where, and how to learn. This autonomy, however, comes with an increased sense of responsibility (Lehmann et al., 2014; Luo et al., 2021; Rakes & Dunn, 2010). Research consistently indicates that the effectiveness of online learning is closely linked to the degree of self-regulated learning (Wong et al., 2019; Zheng, 2016). Kauffman (2004) posits that high levels of self-regulated learning and independence are essential for effective online learning, with low levels potentially leading to reduced effectiveness. Indeed, concerns have been raised about the relatively high rates of attrition and non-completion in online learning (Bawa, 2016). Meta-analyses also affirm the importance of self-regulated learning in online education (Broadbent & Poon, 2015).

The robust correlation between self-regulated learning and student achievement prompts exploration into how self-regulated learning behavior develops over time. A growing body of literature investigates whether online learning environments can actively foster self-regulated learning skills, rather than merely serving as passive settings for research (e.g., Luo et al., 2021). Compared to traditional learning environments, online learning settings are thought to offer learners richer and more diverse resources, overcoming the constraints of time and space (Wang, 2008), and providing opportunities for self-regulated learning (Greene & Azevedo, 2009). Additionally, it is postulated that metacognitive activities and mechanisms promoting self-assessment within online learning environments have the potential to enhance self-regulated learning skills (Cho & Heron, 2015; Yukselturk & Bulut, 2007).

2.1.1.1 Changes in self-regulated learning over time Although online contexts hold potential for improving self-regulated learning, research on its developmental patterns within these environments remains limited. Many studies have primarily focused on changes in students' self-perceptions of self-regulated learning behaviors in face-to-face classroom settings. For instance, a study of medical students in South Korea assessed cognitive and metacognitive strategy use using the Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich et al., 1993). The study identified a significant decline in self-regulated learning strategies from the first to the second year of a four-year basic medical sciences program (Kim & Jang, 2015). A similar pattern was observed among Australian medical students, showing decreases in metacognitive

self-regulation over 10 weeks during introductory lectures before their first clinical placement (Cho et al., 2017).

Longitudinal studies on school-aged adolescents have found similar results. Middle school students in the 7th grade completed MSLQ items assessing their self-regulatory strategies in mathematics three times over a school year (Ahmed et al., 2013). The analyses revealed a general declining trend in both shallow (i.e., rehearsal) and deep strategies (i.e., elaboration, organization), as well as metacognitive strategies (i.e., planning, monitoring, evaluation). High school students in Finland also showed a decreasing pattern of perceived self-regulation, measured using the Inventory of Learning Styles (Vermunt, 1992), from the first to the third year of study (Helle et al., 2013). Interestingly, a study of US adolescents from grades 5 to 11 categorized students into four distinct groups: Steady Decline, Elevated, Late Onset, and Pronounced Decline. The largest group, Steady Decline, comprised 82% of the total students. Combining the two groups showing a decline (i.e., Steady Decline and Pronounced Decline), approximately 88% of the total sample exhibited a decrease. These findings indicate a predominant trend of declining self-regulated learning behaviors from elementary to high school across diverse cultural contexts (e.g., Caprara et al., 2008; Mok et al., 2007; Pajares & Valiante, 2002).

This trend corresponds with the consistent phenomenon of declining motivation, attributed to changes in the academic and social environments of schools. Increasing difficulty, heightened responsibilities, and more competitive atmospheres may result in lower motivation and self-regulation as students progress to higher grade levels (Fredricks & Eccles, 2002; Jacobs et al., 2002; Robinson et al., 2019). Consequently, one might expect a similar decline in self-reported self-regulated learning behavior scores in online programs over time. However, it has been suggested that voluntary participation in online programs may enhance students' self-regulated learning skills, as such environments foster opportunities for self-regulation (Azevedo et al., 2004; Greene & Azevedo, 2009). Some studies providing interventions or training to support self-regulated learning have reported improvements in students' self-regulation. However, these studies differ from the current study's purpose, as they focus on the effects of specific interventions rather than natural online teaching and learning contexts (e.g., Dörrenbächer & Perels, 2016; Jansen et al., 2020). This study specifically examines how self-regulated learning develops during an inquiry-based mathematics and science online program, providing insights into natural developmental patterns in online settings.

2.2 Basic psychological needs satisfaction and self-regulated learning

Basic psychological needs theory is a mini-theory within self-determination theory. The satisfaction of basic psychological needs means the fulfillment of fundamental psychological requirements that are essential for individuals to maintain well-being (Deci & Ryan, 2000). This theory posits that three basic psychological needs—autonomy, competence, and relatedness—are crucial for psychological well-being and optimal functioning (Ryan & Deci, 2020). *Autonomy* is defined as a sense of

initiative and ownership over actions, supported by meaningful experiences that spark interest but hindered by external controls. *Competence* refers to the sense of mastery, fostered in structured environments with optimal challenges and positive feedback. Lastly, *relatedness* is feelings of connectedness and belonging, nurtured through expressions of respect and care (Ryan & Deci, 2020). While self-determination theory has been extensively applied in traditional face-to-face environments, its application in online learning contexts has not received as much attention (Hsu et al., 2019). Ryan and Deci (2020) recommend that future research should focus more on how educational media, e-learning, remote classrooms, and other opportunities afforded by technology can be designed to motivate engagement and learning. Researchers suggest that self-regulated learning requires students to be self-motivated (Kuo et al., 2014). Thus, basic psychological needs theory can provide insights into how students develop motivation, which is closely linked to their use of self-regulated learning strategies in online educational contexts.

The need for autonomy involves perceiving oneself as the origin and regulator of one's actions (Deci & Ryan, 2000). In self-regulated learning, autonomous learners are more inclined to set personal learning objectives, seek resources, and engage proactively in their learning journey (Chen & Jang, 2010; Xie et al., 2006). The need for competence involves achieving mastery and proficiency in tasks and feeling effective in interacting with the environment (Deci & Ryan, 2000). This need is closely linked to self-efficacy, the belief in one's ability to accomplish tasks successfully (Schunk & DiBenedetto, 2014). Competent learners are more likely to undertake challenging tasks, persevere through difficulties, and use effective learning strategies (Schunk & DiBenedetto, 2014). The need for relatedness involves feeling a sense of belonging and connection with others (Deci & Ryan, 2000). Learners who feel connected are more inclined to seek assistance, exchange ideas, and collaborate (Roorda et al., 2011). This social support enhances engagement and perseverance, key aspects of self-regulated learning.

Despite theoretical expectations highlighting the importance of satisfying students' basic psychological needs in self-regulated learning, only a few studies have directly applied this theory to self-regulated learning. In online learning, a mixed-methods study assessed undergraduate students' perceived autonomy, measured by the degree of choice in a course, and engagement, indicated by login frequency and discussion board participation (Xie et al., 2006). Results showed a positive correlation between perceived autonomy and course engagement, suggesting that meeting students' autonomy needs supports their self-regulated learning in online settings. Another study in online programs for renewable teaching certificates demonstrated that contextual support for students' autonomy and competence predicted both the time spent studying weekly and the frequency of accessing online content through their satisfaction of psychological needs in online classes (Chen & Jang, 2010).

Previous studies highlight the positive link between the satisfaction of autonomy, competence, and relatedness needs and self-regulated learning in online settings, focusing mainly on how teaching practices that address these needs enhance learning behaviors. However, our study views these needs as personal-level psychological variables rather than contextual variables, given the unique characteristics of online learning environments, which lack physical teacher presence and shared physical

spaces among learners. We hypothesize that the role of needs satisfaction in online learning environments will be similar to that in traditional classroom settings. Building on this, we aim to dissect the individual contributions of each basic psychological need to self-regulated learning development, noting that prior research often overlooks their separate effects. Particularly in online learning, autonomy's role is deemed crucial due to the reliance on self-motivation (Lehmann et al., 2014; Luo et al., 2021; Rakes & Dunn, 2010). Additionally, our longitudinal study seeks to understand how satisfaction of these needs influences self-regulated learning over time, especially during significant developmental periods like adolescence (Gestsdóttir & Lerner, 2008). We will leverage longitudinal data to examine the trajectory of self-regulated learning in relation to basic psychological needs.

2.3 Consideration of academic achievement levels

Academic achievement refers to the level of performance in their educational endeavors, measured through grades, test scores, or skill mastery (Zuffiano et al., 2014). It is regarded as a key predictor of students' future career prospects and educational pathways, surpassing even cognitive abilities and intelligence. Much research has been done on achievement differences in the development of self-regulated learning, particularly in studies that have provided self-regulated learning interventions and analyzed their effects. However, existing literature presents mixed results and interpretations. Some studies report that the increase in self-regulated learning is greater for high achievers. High achievers benefit the most from self-regulated learning support due to their higher initial levels of self-regulation, which enable better cognitive control and easier application of learning strategies (Bannert et al., 2014; He et al., 2024; Otto & Kistner, 2017). Conversely, other studies suggest that low achievers benefit more from self-regulated learning support by learning and practicing newly acquired self-regulated learning skills, while high achievers with already high levels of self-regulated learning have less room for development (González-Pienda et al., 2014). Additionally, it is argued that intermediate achievers, who possess some self-regulated learning skills but are less adept in strategy use, may benefit more from self-regulated learning support than students lacking these skills entirely (Barnard-Brak et al., 2010; Dörrenbächer & Perels, 2016). In sum, there is no consistent evidence on how students' achievement levels relate to the effects of self-regulated learning interventions.

Additionally, while the satisfaction of basic psychological needs for autonomy, competence, and relatedness is theoretically universally essential for optimal functioning in humans, transcending cultural and individual differences (Ryan & Deci, 2020), some researchers suggest that students facing academic challenges, particularly those identified as low-achieving, may benefit more from environmental support for these psychological needs. Low-achieving students often have lower competence levels in academic tasks, making an increase in perceived competence particularly impactful for their success. In contrast, high-achieving students, who already perceive themselves as successful in class, may derive greater benefits from the satisfaction of other needs, such as autonomy and relatedness.

Despite such expectations, the extent to which the satisfaction of basic psychological needs varies in its importance has not been extensively explored empirically. However, literature suggesting more substantial positive effects of a growth mindset on academic behavior in low-achieving students compared to typical-achieving students (Burnette et al., 2013, 2023) hints at the potentially greater significance of satisfying the basic psychological needs for academically challenged students. Given the close link between low academic achievement and competence needs satisfaction, addressing these needs may be particularly critical for fostering self-regulated learning, even though all three needs contribute to the process.

As self-regulated learning research continues to report a positive association between levels of self-regulated learning and achievement, it is hypothesized that the development of self-regulated learning would also differ across achievement groups. It is worth examining whether the role of basic psychological needs in the development of self-regulated learning differs across achievement groups. Based on previous research, it is expected that the satisfaction of basic psychological needs, especially the need for competence, would play a positive role in the development of self-regulated learning among low-achieving students.

From a theoretical perspective, this research could provide a more detailed understanding of the universality claim in basic psychological needs theory, specifically regarding the varying roles of basic psychological needs satisfaction in academic behaviors across different achievement levels in learning contexts. Practically, the findings could inform strategies to foster student engagement and self-regulated learning in online environments, while identifying those who may benefit the most from tailored support.

2.4 The present study

This study aims to investigate the trajectories of students' self-regulated learning in an online course and to examine how the satisfaction of their basic psychological needs shapes these trajectories. Specifically, the following research model is hypothesized and validated based on prior studies: First, students' self-regulated learning is expected to develop within an online class. Studies on the developmental patterns of self-regulated learning have reported that self-regulated learning patterns change in both short-term and long-term educational contexts (e.g., Caprara et al., 2008; Mok et al., 2007; Pajares & Valiante, 2002). Moreover, researchers in online learning have suggested that the online learning environment itself can enhance self-regulated learning strategies and skills (Azevedo et al., 2004; Greene & Azevedo, 2009). Accordingly, this study investigates how students' self-regulated learning evolves throughout a 12-week online course.

Second, the development of self-regulated learning is hypothesized to be associated with the satisfaction of basic psychological needs. Existing research has demonstrated significant relationships between basic psychological needs (autonomy, competence, and relatedness) and self-regulated learning in online learning contexts (e.g., Bai & Gu, 2022; Hidayatullah & Csíkos, 2023; Zhou et al., 2021). Thus, this

study investigates how the development of self-regulated learning during an online course relates to students' satisfaction of these basic psychological needs.

Third, the relationship between self-regulated learning development and the satisfaction of basic psychological needs is expected to vary by students' achievement levels. Research analyzing the effects of self-regulated learning support programs has shown that the development of self-regulated learning differs across achievement groups (e.g., Bannert et al., 2014; Dörrenbächer & Perels, 2016; González-Pienda et al., 2014). Additionally, studies emphasize that the satisfaction of basic psychological needs is particularly crucial for low-achieving students (Burnette et al., 2013, 2023). Therefore, this study explores how the satisfaction of basic psychological needs influences the development of self-regulated learning across different achievement groups. To address these objectives, this study specifically examines the developmental patterns of self-regulated learning among elementary and middle school students during a 12-week online course. It also determines the influence of students' perceptions of autonomy, competence, and relatedness on these developmental trajectories. Furthermore, it investigates whether the relationship between the satisfaction of basic psychological needs and the trajectories of self-regulated learning differs by students' achievement levels. The specific research questions guiding this study are as follows:

First, what are the overall trajectories of students' self-regulated learning in an online course?

Second, does students' satisfaction of the basic psychological needs (autonomy, competence, relatedness) relate to the growth trajectory of self-regulated learning in an online course?

Third, do the growth trajectories of self-regulated learning and the effects of the basic psychological needs vary by students' achievement levels (low, intermediate, and high)?

3 Methods

3.1 Participants and research context

Data from 1,105 elementary and middle school students—697 elementary (grades 5–6, 63.1%) and 408 middle school students (grades 7–9, 36.9%), comprising 692 males (62.6%) and 413 females (37.4%)—were used for this study. These students participated in an online learning program designed and provided by a university, a science and technology-focused institution in South Korea, for K-12 students with a keen interest in mathematics and science. This program took place during the Fall semester of 2022. This online program, designed for both elementary and middle school students, focused on teaching fundamental concepts in mathematics and science and included six Problem-Based Learning (PBL) tasks to address real-world issues over 12 weeks. The content was delivered in an e-Book format, designed to encourage students to independently explore and solve tasks for each topic, rather than passively acquiring basic mathematical and scientific knowledge.

All e-Book content consists of three sections: Problem Exploration, introducing real-life problems to enhance motivation; Concept Learning, providing key concepts and resources for independent study; and Problem-Solving, where students apply their knowledge to complete tasks and submit their findings as reports. For instance, the program for first-year middle school students included six real-life topics: "How is Research Conducted?", "Can Artificial Intelligence Become Human?", "The Era of Gene Editing", "Let's Determine Traffic Signal Timing", "The Present and Future of Electric Vehicles", and "Generating Energy Through Human Movement: Energy Harvesting Technology." These problem-based learning contents were provided over 12 weeks, with six for each grade level. Students independently accessed the online content through the Learning Management System (LMS) and studied at their own pace. A detailed content example is provided in Supplementary A. To join the online education program, students had to register as members. During the registration process, both students and their guardians consented to the collection and protection of personal data and its use for research purposes. The data collection process adhered to the ethical standards for research established at the national level (Choi et al., 2023). All participants were informed about the study's objectives and requirements prior to their participation.

Throughout the study, participants received regular reminders to complete the survey via direct messages sent through the LMS. The study achieved a completion rate of 66%. Although this may appear modest, it surpasses typical completion rates reported in online survey-based studies (Cook et al., 2000; Wu et al., 2022). Factors such as academic obligations and time constraints likely influenced participation, particularly given the study's 12-week duration and four time-point measurements.

3.2 Measures

3.2.1 Self-regulated learning

The self-regulated learning scale developed by Bong et al. (2012) was administered at four-week intervals: prior to the program, four weeks after its start, eight weeks after its start, and at the program's conclusion. The scale comprises 8 items, such as "I plan how much time and effort to invest in studying" and "I choose appropriate learning strategies depending on the situation" (See Table 9 in Appendix for the full list of items). Each item was rated on a 7-point Likert scale, ranging from 1 (not at all) to 7 (strongly agree). Inter-item reliability coefficients (Cronbach's alpha) ranged from 0.897 to 0.927 across the different measurement points.

Confirmatory factor analysis of the single-factor model across the eight items indicated good model fit at all four time points (see Table 1). Longitudinal measurement invariance tests revealed that the configural invariance model provided the best fit, confirming that the factor loadings of each item remained equivalent across the four time points. While adding the requirements for metric, scalar, and strict invariance consistently reduced model fit, the scalar invariance model maintained acceptable fit indices, with CFI and TLI within acceptable ranges and RMSEA below 0.05. This supports the assumption of equivalence in item intercepts and variances across

Table 1 Confirmatory Factor Analyses (CFA) and longitudinal measurement invariance tests for self-regulation learning

	χ^2	<i>df</i>	$\Delta\chi^2(df)$	CFI	TLI	SRMR	RMSEA 90% CI
CFA							
Time1	183.56	20	-	0.964	0.949	0.026	0.075, 0.098
Time2	144.30	20	-	0.969	0.957	0.024	0.072, 0.098
Time3	113.58	20	-	0.971	0.960	0.025	0.069, 0.099
Time4	142.58	20	-	0.969	0.957	0.024	0.078, 0.106
Measurement invariance test							
Configural invariance	1109.66	410	-	0.962	0.954	0.034	0.037, 0.042
Metric invariance	1157.58	431	47.92*** (21)	0.961	0.955	0.041	0.036, 0.042
Scalar invariance	1350.81	455	193.23*** (24)	0.952	0.947	0.051	0.040, 0.045
Strict invariance	2064.04	479	713.23*** (24)	0.914	0.911	0.090	0.052, 0.057

the four time points, confirming the comparability of self-regulated learning measurements over these intervals.

3.2.2 Psychological needs satisfaction

Students' psychological needs were assessed once prior to the program began using scales developed by Chen et al. (2015). The scale comprised 18 items: autonomy (e.g., "I feel that I can generally express my thoughts and opinions freely"), competence (e.g., "I feel that I am capable of solving the tasks given to me"), and relatedness (e.g., "The people around me and I generally help each other") (see Table 9 in Appendix for the full list of items). Each item was rated on a 6-point Likert scale ranging from 1 (not at all) to 6 (strongly agree). Reliability coefficients (Cronbach's alpha) were 0.749 for autonomy, 0.806 for competence, and 0.832 for relatedness. Descriptive statistics and variable correlations are presented in Table 2.

3.2.3 Achievement

Academic achievement was measured by averaging the scores of six assignment reports submitted by students over a 12-week period. Students completed inquiry-based and problem-solving projects, submitting their work as individual reports.. The scoring rubric for each report was designed by subject matter experts using the online problem-based science learning evaluation criteria established by Choi et al. (2017). These criteria outline five key evaluative elements: scientific knowledge, logical and analytical thinking, inquiry skills, problem-solving abilities, and creative thinking. General assessment guidelines are provided for each element, and these guidelines were adapted and reorganized for each topic to align with the specific cognitive skills and content relevant to the respective inquiry tasks. A scoring rubric example is provided in Supplementary B. The raters were undergraduate and graduate students majoring in science. Before scoring each topic, they participated in a

Table 2 Descriptive statistics

Variables	M	SD	Min	Max	Skewness	Kurtosis	Correlations						
							1	2	3	4	5	6	7
1. Self-regulated learning_T1	5.09	1.20	1.00	7.00	-0.46	3.09	1.00						
2. Self-regulated learning_T2	5.41	1.07	1.13	7.00	-0.57	3.19	0.66***	1.00					
3. Self-regulated learning_T3	5.48	1.04	1.00	7.00	-0.45	2.80	0.62***	0.71***	1.00				
4. Self-regulated learning_T4	5.50	1.05	1.00	7.00	-0.52	3.02	0.58***	0.68***	0.75***	1.00			
5. Autonomy_T1	4.17	0.63	2.17	6.00	-0.24	2.60	0.43***	0.34***	0.34***	0.31***	1.00		
6. Competence_T1	4.86	0.80	1.83	6.00	-0.62	3.14	0.50***	0.43***	0.42***	0.46***	0.52***	1.00	
7. Relatedness_T1	4.94	0.82	1.67	6.00	-0.74	3.30	0.36***	0.29***	0.32***	0.32***	0.44***	0.60***	1.00
8. Achievement	66.97	20.00	0.00	99.83	-0.92	3.40	0.15***	0.18***	0.12**	0.14***	0.08***	0.09***	0.08*

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

one-hour training session to understand the content, characteristics of the specific inquiry tasks, and scoring criteria. During each session, the raters graded sample reports for the topic, and their results were reviewed by experts, including doctoral-level education professionals with over five years of experience in developing and managing this program and its scoring processes. All six assignment scores were out of 100 points, with an average final achievement score of 67.0 and a standard deviation of 20.0. The final scores were positively and significantly correlated with self-regulated learning and psychological need satisfaction, as shown in Table 2. Additionally, the correlation with course satisfaction was 0.13, which was also positive and statistically significant.

Students were divided into three achievement level groups based on tertiles of the final scores: low-achieving (first tertile), intermediate-achieving (second tertile), and high-achieving (third tertile). The cut scores that segmented the score distribution into these groups were 62.6 and 77.8. Normative scoring clarified the interpretability of group differences and balanced the number of cases in each group, enhancing the stability of estimates in multi-group analyses. The score distributions of each group are presented in Table 5. Additionally, sample student assignments corresponding to the high, medium, and low groups are provided in Supplementary C.

3.2.4 Data analyses

Before the analysis, the normality of individual variable distributions and the homogeneity of variance across groups were examined. As shown in Table 2, all variables displayed negative skewness, but skewness values did not exceed -1 , and the kurtosis values reached a maximum of 3.4, satisfying the assumption of normality. Bartlett's tests (see Table 10 in Appendix) indicated homogeneity of variance across grade levels for all measures except the second measurement of self-regulated learning.

Multilevel models (Raudenbush & Bryk, 2001) were used to examine whether students' self-regulation significantly changed over time after controlling for both personal background and further psychological needs. As time-series self-regulated learning measures were nested in individual students, the multilevel models specified repeated measures (times) as Level-1 and students as Level-2. Linear change patterns in self-regulated learning across four measurement points during the three-month online program were assumed, and the average amount of change over time – increase, decrease, or no change – was estimated. In addition, average effects of gender and grade level (Model 1 in Table 2) were examined. For the estimation, the 'mixed' command in Stata v13.0 was used.

Latent growth curve modeling (Burant, 2016; Ferrer & McArdle, 2003) was subsequently used to identify potential non-linear growth patterns in self-regulated learning. The model specified two growth factors—intercept and slope—and estimated the growth parameters representing the paths from the slope factor to each measurement, indicating the proportion of change across the four measurements at each time point. The slope factor loadings were set to 0 for the very first measure and 1 for the final measure and allowed to be estimated freely for the second and third measures so that the best-fitting shape of the trajectory could

Table 3 Multilevel models for changes in self-regulated learning: effects of time and backgrounds

	Predictors	<i>b</i>	<i>s.e</i>	<i>p</i>
Fixed effect	Time	0.136	0.010	<0.001
	Female	0.296	0.061	<0.001
	School level	0.181	0.062	<0.01
	Constant	4.826	0.049	99.18
Random effect	Between-individual	0.803	0.042	
	Within-individual	0.425	0.013	
ICC (Intra-class correlation)		0.654		
Log-likelihood		−4356.129		

be interpreted from the estimated factor loadings with no forcing or predetermining a specific shape of trajectory. Additionally, the model included paths from basic psychological needs—autonomy, competence, and relatedness—to growth factors, estimating the effects of initial psychological needs levels on the intercept and slope of self-regulated learning changes over time.

Multi-group analyses based on the above growth models were employed to investigate whether students' self-regulated learning growth patterns and effects of the basic psychological needs on the growth patterns are equivalent or differential depending on achievement levels. First, three models were compared to determine the best fit to the data, examining whether growth patterns and the relationship between basic psychological needs and growth patterns significantly differed across the three achievement groups: (1) Model 1 specified different growth and path parameters across groups, (2) Model 2 specified equal growth parameters and different path parameters, and (3) Model 3 specified different growth parameters and equal path parameters (shown in Table 4). Next, the estimated parameters from the best-fitting model were compared to clarify how growth patterns and the effects of basic psychological needs differ across achievement levels (see Table 5). Mplus version 7 (Muthén & Muthén, 2015) was used for constructing and estimating the latent growth models and multi-group analyses.

Table 4 Latent growth model comparisons of self-regulated learning

	χ^2	<i>df</i>	CFI	TLI	SRMR	RMSEA 90% C.I
No change model	180.64	8	0.893	0.919	0.066	0.122, 0.158
Linear change model	36.77	5	0.980	0.976	0.043	0.054, 0.100
Basis coefficient model	2.54	3	1.000	1.000	0.028	0.000, 0.048
Quadratic change model	6.78	1	0.996	0.978	0.017	0.029, 0.128

Table 5 Latent growth model estimates for self-regulated learning: non-linear growth pattern

		<i>Estimates</i>	<i>s.e</i>	<i>p</i>	β
Patterns of change in self-regulated learning over time	Mean of intercept	0.393	0.235	0.095	0.346
	Mean of slope	1.715	0.247	<0.001	0.675
	Variance of intercept	0.867	0.150	<0.001	2.137
	Variance of slope	0.611	0.161	<0.001	0.949
	Slope \rightarrow ASR2	0.741	0.060	<0.001	0.541
	Slope \rightarrow ASR3	0.907	0.044	<0.001	0.697
	Slope \rightarrow ASR4	1.000	-	-	0.759
Effects of satisfaction with basic psychological needs	Autonomy \rightarrow Intercept	0.410	0.057	<0.001	0.229
	Competence \rightarrow Intercept	0.548	0.051	<0.001	0.385
	Relatedness \rightarrow Intercept	0.065	0.047	0.168	0.047
	Autonomy \rightarrow Slope	-0.176	0.060	0.003	-0.139
	Competence \rightarrow Slope	-0.121	0.053	0.023	-0.120
	Relatedness \rightarrow Slope	0.001	0.049	0.976	0.002
Correlation between intercept and slope		-0.598	0.089	<0.001	-

4 Results

4.1 Overall trajectory of students' self-regulated learning

We first fit the data to a multilevel model to examine whether measurement time points and basic background variables significantly predicted students' self-regulated learning. The results, presented in Table 3, indicate that students' self-regulated learning scores increased by an average of 0.136 per measurement ($s.e. = 0.010$, $p < 0.001$), assuming a linear change over time after controlling for gender and school level. The between-student variance was 0.803 and the ICC was 0.654, indicating significant variability in the estimated mean change. Female students scored higher on self-regulated learning on average than male students, and middle school students scored higher than elementary school students. Next, a series of latent growth curve models, presented in Table 4, were evaluated to identify the model that best explained changes in self-regulated learning over time. The no-change model was clearly not supported, aligning with the multilevel model results that showed a significant time effect. Among the three different models – linear change, quadratic change, and basis coefficient—the basis coefficient model, which estimated the proportions of total change at each time point based on the data, demonstrated the best fit. The chi-square value of the basis coefficient model was significantly smaller than that of the linear change model ($\Delta\chi^2 = 24.3$, $\Delta df = 2$, $p < 0.001$), indicating that the basis coefficient model better represents the change and interdependence among the four repeated measures of self-regulated learning. The chi-square difference between the basis coefficient and quadratic change models was not significant ($\Delta\chi^2 = 4.24$, $\Delta df = 2$, $p = 0.880$), suggesting that the basis coefficient model is parsimonious and provides a comparable fit to the quadratic change model. Consequently, subsequent analyses were conducted using the basis coefficient model. According to the

slope parameters estimated in the basis coefficient model, students' self-regulated learning increased by an average of 0.41 points across four measurement points. By the second measurement, 71% of the total increase had occurred, and by the third measurement, 89% of the total increase had been achieved. This pattern indicates that although self-regulated learning increased over time, the rate of increase progressively diminished, reflecting a non-linear growth trajectory in students' self-regulated learning throughout the online course.

4.2 Relationship between students' satisfaction of basic psychological needs and the growth trajectory of self-regulated learning

Basic psychological needs were incorporated into the latent growth model of self-regulated learning from the previous analysis to investigate how students' satisfaction with these needs influences changes in self-regulated learning. The estimated latent growth model demonstrated a good fit with the data: $\chi^2=10.05$ ($df=9$, $p=0.347$), RMSEA=0.010, 90%CIs [0.000, 0.036], CFI=0.999, TLI=0.999, SRMR=0.024. The estimated parameters are presented in Table 5.

First, the growth pattern of self-regulated learning revealed an average slope estimate of 1.715 over three months, indicating a significant increase in self-regulated learning despite notable between-individual variance ($b=0.867$, $s.e.=0.150$, $p<0.001$). Approximately 74% of the total increase occurred between the first and second measurements (slope factor loading to the second measure=0.741, $s.e.=0.060$, $p<0.001$); 16% occurred between the second and third time points; and the final 10% occurred between the third and last measurements, illustrating a distinct non-linear growth pattern in self-regulated learning.

Second, the associations of autonomy, competence, and relatedness with the two growth parameters—the intercept and slope—were examined. For the intercept, autonomy and competence significantly predicted the initial level of self-regulated learning, whereas relatedness did not exhibit unique explanatory power. This indicates that students with higher levels of autonomy and competence tend to have higher initial values of self-regulated learning at the beginning of the program. For the slope, both autonomy and competence were found to decelerate the increase in self-regulated learning, as their negative coefficients implied. Similarly, relatedness was not associated with changes in self-regulated learning.

4.3 Effects of basic psychological needs on the growth trajectories of self-regulated learning across different achievement levels

Table 6 presents the distributions of self-regulated learning and psychological needs satisfaction scores by achievement level. The higher-achieving group tended to exhibit higher average self-regulated learning scores and greater satisfaction of basic psychological needs, with slightly smaller inter-individual variation within the group. Multi-group analyses were conducted to examine whether changes in self-regulated learning varied across high-, intermediate-, and low-achieving groups, and whether basic psychological needs (autonomy, competence, and relatedness)

Table 6 Self-regulated learning and the basic psychological needs satisfaction by achievement levels

Variables	Low		Intermediate		High	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Achievement	43.86	15.24	70.87	4.24	86.24	5.39
Self-regulated learning_T1	4.83	1.27	5.07	1.17	5.35	1.10
Self-regulated learning_T2	5.09	1.18	5.39	1.01	5.66	0.98
Self-regulated learning_T3	5.26	1.11	5.42	1.07	5.68	0.95
Self-regulated learning_T4	5.26	1.14	5.48	1.03	5.66	1.00
Autonomy_T1	4.11	0.64	4.12	0.64	4.28	0.60
Competence_T1	4.78	0.82	4.82	0.80	4.98	0.77
Relatedness_T1	4.84	0.85	4.94	0.81	5.03	0.78

had differential effects on these changes. Initially, all growth parameters and path parameters from the basic psychological needs to the growth parameters were freely estimated across the three groups. The intercept for the low-achieving group was estimated as negative and non-significant. For interpretability, we fixed this parameter to zero. The model (Model 1) fit is shown in the first row of Table 7. Model 1, where the growth and path parameters are estimated differently and freely for the three achievement groups, shows a good overall fit.

In Model 2, the growth parameters, including the means of intercept and slope, as well as the slope loadings, were constrained to be equal across the high-, intermediate-, and low-achieving groups, while the path parameters (regression coefficients from the basic psychological needs to latent intercept and slope) were freely estimated for each group. As shown, the model fit significantly deteriorated from Model 1 ($\Delta\chi^2 = 18.62$, $df = 3$, $p < 0.001$). For Model 3, unlike Model 2, the path parameters were estimated the same across groups, but the growth parameters were estimated separately across groups. Again, the model fit of Model 3 was significantly worse than Model 1 ($\Delta\chi^2 = 228.55$, $df = 11$, $p < 0.01$). These results indicate that Model 1 best captures the differential relationship between psychological needs and changes in self-regulated learning across the three groups. The estimated parameters of the final model, Model 1, are shown in Table 8. The change patterns of student self-regulated learning substantially differentiated across groups. Although self-regulated learning increased on average over

Table 7 Comparisons among multigroup latent growth models

	$\chi^2(df)$	$\Delta\chi^2(\Delta df)$	RMSEA 90% C.I.	CFI	TLI	SRMR
Model 1	28.59(32)		0.000 (0.000, 0.033)	1.000	1.000	0.055
Model 2 (Equal growth parameters)	47.21(35)	18.62*** (3)	0.000 (0.000, 0.052)	0.994	0.990	0.070
Model 3 (Equal path parameters)	57.14(43)	28.55** (11)	0.000 (0.000, 0.049)	0.993	0.991	0.066

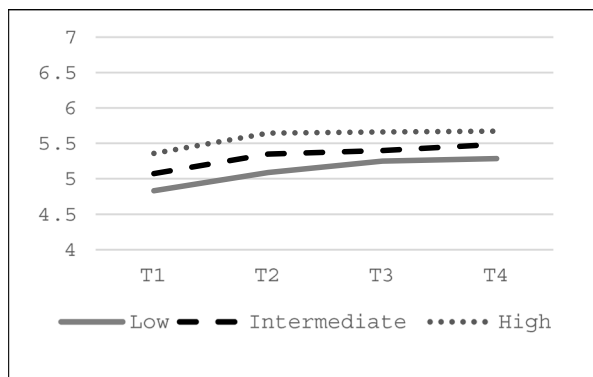
Table 8 Multigroup latent growth model estimates for achievement levels

	Low achieving group			Intermediate achieving group			High achieving group		
	<i>b</i>	<i>s.e</i>	<i>p</i>	<i>b</i>	<i>s.e</i>	<i>p</i>	<i>b</i>	<i>s.e</i>	<i>p</i>
Patterns of change in self-regulated learning over time									
Mean of intercept	0.000	-	-	1.048	0.415	0.011	0.764	0.409	0.06
Mean of slope	1.404	0.385	<0.001	2.032	0.458	<0.001	1.502	0.401	<0.001
Variance of intercept	0.848	0.129	<0.001	0.848	0.129	<0.001	0.848	0.129	<0.001
Variance of slope	0.644	0.138	<0.001	0.644	0.138	<0.001	0.644	0.138	<0.001
Slope → ASR2	0.568	0.101	<0.001	0.666	0.081	<0.001	0.910	0.053	<0.001
Slope → ASR3	0.924	0.081	<0.001	0.786	0.067	<0.001	0.968	0.055	<0.001
Slope → ASR4	1.000	-	-	1.000	-	-	1.000	-	-
Effects of basic psychological needs satisfaction									
Autonomy → Intercept	0.663	0.090	<0.001	0.272	0.095	0.004	0.229	0.098	0.019
Competence → Intercept	0.562	0.086	<0.001	0.479	0.088	<0.001	0.170	0.079	<0.001
Relatedness → Intercept	-0.119	0.075	0.114	0.122	0.083	0.141	0.551	0.085	0.031
Autonomy → Slope	-0.268	0.118	0.023	-0.209	0.103	0.042	-0.020	0.096	0.830
Competence → Slope	-0.135	0.107	0.209	0.008	0.096	0.936	-0.212	0.082	0.010
Relatedness → Slope	0.165	0.095	0.082	-0.161	0.090	0.074	-0.007	0.079	0.932
Correlation between intercept and slope	-0.622	0.087	<0.001	-0.584	0.090	<0.001	-0.654	0.070	<0.001

Note. This model showed reasonably good fit showing: $\chi^2 = 28.59$ ($df = 32$, $p = 0.640$), RMSEA = 0.000, 90% C.I. = [0.000, 0.033], CFI = 1.000, TLI = 1.000, SRMR = 0.055

time for all three groups, the intermediate-achieving group's slope ($b=2.032$, $s.e.=0.458$, $p<0.001$) is noticeably larger than those of the low- and high-achieving groups. Additionally, while the initial increase between the first and second measurements was the largest in all three groups, the ratio of the initial increase to the total increase varied among the groups. For high achievers, over 90% of their total growth occurred between the first and second time points, followed by minimal increases thereafter. For the low-achieving group, about 56% of their total change was observed between the first and second time points, with a 36% change between the second and third time points, resulting in over 90% of their total growth by the third measurement. Meanwhile, the intermediate-achieving group achieved 66% of their total growth in self-regulated learning early on, with 12% growth between the second and third time points, and 22% growth between the third and fourth time points, showing a steady increase throughout the course. Figure 1 illustrates the mean changes in self-regulated learning by group, as estimated from the final model. The effects of basic psychological needs satisfaction varied by group. For the low-achieving group, autonomy and competence significantly predicted the intercept of self-regulated learning, with substantial coefficient sizes: for every one-point increase in autonomy and competence, the initial level of self-regulated learning increased by an average of 0.66 and 0.56 points, respectively. In the high-achieving group, while autonomy and competence were still significant predictors, relatedness showed the largest effect on their initial level of self-regulation. In both the low- and intermediate-achieving groups, autonomy negatively affected the increase in self-regulated learning, implying that students with lower initial autonomy had a higher average growth rate. In the high-achieving group, competence reduced the rate of increase in self-regulated learning, suggesting that students with lower initial competence benefited more from self-regulated learning growth in the online program.

Fig. 1 Estimated mean changes over time by achievement levels



5 Discussions

The purpose of this study was to determine whether students' self-regulated learning increases consistently throughout an online course and to investigate the role of basic psychological needs in changes to self-regulated learning. The self-regulated learning questionnaire was administered to 1,105 elementary and middle school students participating in an online inquiry-based mathematics and science program four times over a 12-week period: before, during, and after the course. The basic psychological needs questionnaire was administered before the course. For the analysis of the collected data, both multilevel models and latent growth curve modeling techniques were employed. The major findings of this study are summarized as follows.

5.1 Increase in students' self-regulated learning over the online course

Over the 12-week online course, self-regulated learning scores showed significant changes over time, which were found to be nonlinear rather than linear. Specifically, approximately 74% of the total increase in self-regulated learning occurred between the first and second measurements, 16% occurred between the second and third time points, and the remaining 10% occurred between the third and final measurements. This suggests that self-regulated learning develops rapidly during the initial stages of online learning and slows down progressively over time.

This study identified a pattern of increasing self-regulated learning within online learning environments. However, research on the development of self-regulated learning in various cultural contexts has reported a pattern of decline with increasing levels of schooling or over time within a course or class (e.g., Caprara et al., 2008; Mok et al., 2007; Pajares & Valiante, 2002). Most of these studies were conducted in face-to-face classroom settings. However, studies that have provided interventions or training to support self-regulated learning have found that students' self-regulated learning tends to increase (e.g., Dörrenbächer & Perels, 2016; Jansen et al., 2020).

The present study demonstrated a sustained increase in self-regulated learning over the 12-week online learning period, supporting the argument that online learning environments can enhance students' development of self-regulated learning, as suggested by previous researchers (e.g., Azevedo et al., 2004; Greene & Azevedo, 2009). Although this study did not directly provide interventions to support self-regulated learning, our findings may offer initial evidence for the positive contribution of self-regulated learning experiences required in an online environment to the development of self-regulated learning.

In this online learning context, students completed problem-solving assignments and submitted reports every two weeks. This required a high level of self-regulated learning strategies, including problem identification, planning, conducting research, seeking assistance when necessary, and timely completion and submission of reports. Additionally, students were provided with a dashboard to monitor

their learning engagement, while tutors continuously encouraged engagement and timely submission of assignments. Thus, these activities helped students manage their learning over time, which in turn promoted self-regulated learning. In addition, as demonstrated in previous research (e.g., Kizilcec et al., 2017; Littlejohn et al., 2016), the high motivation and interest of students who voluntarily participated in the online mathematics and science program may have contributed to the development of their self-regulated learning.

An interesting finding from this study is that the increase in self-regulated learning occurred mostly in the initial period. In this online learning context, one-third of the total increase in self-regulated learning took place between the first and second time points. This could be interpreted as students initially trying to adapt to a learning environment that required high self-regulation by utilizing various self-regulated learning strategies. As a result, most of the increase in self-regulated learning occurred early on and then slowed down. Therefore, the study found a steady increase in learners' self-regulated learning within an online course, with most of this increase occurring early in the online class.

5.2 Role of basic psychological needs satisfaction in changes in students' self-regulated learning

This study found that autonomy and competence were significant predictors of initial levels of self-regulated learning, whereas relatedness had no significant effect. In terms of changes in self-regulated learning, both autonomy and competence decreased the growth in self-regulated learning. These results suggest that students with high autonomy and competence start with higher initial self-regulated learning scores but experience smaller changes within an online learning environment. Relatedness did not significantly influence either the initial scores or changes in self-regulated learning. It is well-documented that autonomy and competence influence students' engagement in self-regulated learning. Research suggests that students engage more in self-regulated learning when they perceive autonomy in choosing their behavior (e.g., Bai & Gu, 2022; Schuitema et al., 2016) and exhibit higher self-regulated learning when they believe they are capable of performing well (e.g., Xia et al., 2023). Although relationships have been shown to positively influence self-regulated learning (Hidayatullah & Csikos, 2023), this effect was not significant in our study. This finding might be attributed to the more indirect role of relatedness satisfaction in self-determined behavior compared to autonomy and competence satisfaction (Ryan & Deci, 2020). Although all three basic psychological needs are crucial for self-determined motivation and behavior, when comparing the satisfaction of these needs in a single model, relatedness could have a relatively weaker effect on subsequent outcomes. Our findings confirm the relative roles of basic psychological needs satisfaction in self-regulated learning.

Interestingly, students with high autonomy and competence exhibited lower increases in self-regulated learning in this study. This finding may be associated with the ceiling effect (Edwards & Soland, 2024), in which participants reach the highest possible scores in autonomy, competence, or self-regulated learning, limiting the ability to detect significant positive relationships between variables. For example, high levels of autonomy or competence leave little room for further increases in self-regulated learning.. This phenomenon may be related to the unique characteristics of the participants in this study, who were highly motivated students in this science program. Future research needs to investigate this possibility with other student groups.

5.3 Differential growth patterns of self-regulated learning and the role of basic psychological needs satisfaction across achievement levels

When the development of students' self-regulated learning was analyzed by achievement group, growth patterns varied across academic achievement levels. On average, self-regulated learning increased over time across all groups, but the intermediate-achieving group exhibited a steeper growth slope compared to the low- and high-achieving groups. Although the initial increase between the first and second measurements was the largest across all groups, the proportion of the initial increase relative to the total increase varied. For the high-achieving group, over 90% of the total growth occurred between the first and second time points, with minimal increases thereafter. For the low-achieving group, about 56% of the total change was observed between the first and second time points, with 36% between the second and third time points, achieving over 90% of the total growth by the third measurement. The intermediate-achieving group showed a steady increase throughout the course, with 66% of their total growth early on, 12% between the second and third time points, and 22% between the third and fourth time points.

The patterns of self-regulated learning development across achievement groups largely reflect prior research (Bannert et al., 2014; Barnard-Brak et al., 2010; Dörrenbächer & Perels, 2016; González-Pienda et al., 2014; He et al., 2024; Otto & Kistner, 2017). High-achieving students adapt quickly to online learning environments due to their already high initial self-regulated learning skills, showing the greatest initial growth which is then maintained. This may be due to the repetition of problem-solving-based activities every two weeks. In the low-achieving group, the initial growth rate was modest and declined after a period of increase. The most consistent growth was seen in the intermediate-achieving group, who likely had some self-regulated learning skills and developed them further throughout the study.

The basic psychological needs played varying roles in self-regulated learning across achievement groups. Consistent with previous research (e.g., Bai & Gu, 2022; Schuitema et al., 2016; Xia et al., 2023), autonomy and competence predicted initial values of self-regulated learning in all three groups, regardless of achievement level. By contrast, relatedness significantly predicted the initial value of

self-regulated learning only in the high-achieving group. Furthermore, autonomy influenced changes in self-regulated learning in the low-achieving and intermediate-achieving groups, while relatedness influenced changes in the high-achieving group. Research on the relationship between relatedness and self-regulated learning has been mixed, with some studies finding no direct effect (Xia et al., 2023) and others finding that relatedness contributes to higher achievement through the mediation of self-regulated learning (Zhou et al., 2021). For example, Hidayatullah and Csikos (2023) found that perceived relatedness was related to help-seeking, environmental structuring, and self-evaluation, but not to goal setting and time management.

In this study, the role of relatedness was significant only in the high-achieving group. This online education program was voluntarily selected by talented students across the country, unlike the regular curriculum, and "expanding communication opportunities to satisfy intellectual curiosity" was a key motivation for participation (Park et al., 2020). This motivation was significantly related to online learning engagement and achievement. Therefore, it can be concluded that students with high perceived relatedness participated in the program, influencing their self-regulated learning.

The aforementioned ceiling effect was also observed in the analysis by achievement group. Autonomy mitigated the growth in self-regulated learning in the low-achieving and intermediate-achieving groups, so that students with lower initial autonomy had more growth, while competence mitigated growth in the high-achieving group, so that students with lower initial competence benefited more from online learning.

This study examined how the level of basic psychological needs satisfaction prior to the course influenced self-regulated learning within online learning, but did not examine how basic psychological needs satisfaction changes during online learning. Therefore, it is possible that perceptions of autonomy, competence, and relatedness change within the online learning environment and influence increases in self-regulated learning, which should be explored in future research.

5.4 Theoretical and practical implications

The results of this study provide several theoretical contributions. This study empirically confirmed that participation in online learning itself facilitates the development of self-regulated learning, as argued by online learning researchers. The study also found that growth varied based on individual characteristics, such as achievement, self-perceived autonomy, competence, and relatedness, highlighting substantial individual differences in self-regulated learning growth. These findings provide empirical support for the view of self-regulated learning as a dynamic process (Greene et al., 2021; Winne, 2010) and for the argument that its dynamics stem from interactions with psychological and environmental factors (Pintrich, 2000). The findings also shed light on the role of basic psychological needs in the development

of self-regulated learning in online learning environments. While the roles of basic psychological needs satisfaction and self-regulated learning have each been extensively studied, their interrelated relationship has received little attention.

This study also offers practical implications. The findings suggest that online courses requiring self-regulated activities effectively promote self-regulated learning. Therefore, beyond providing interventions or training to support and develop self-regulated learning, efforts should be made to design and develop online learning courses that inherently require self-regulated behaviors. As students were required to self-regulate their learning, they built on their existing basic self-regulation skills and developed them through repeated practice. However, individual differences in self-regulated learning development suggest that additional support should be tailored to students' initial levels of self-regulated learning, achievement groups, or basic psychological needs. For example, high-achieving students may benefit from more challenging learning activities to continue developing their self-regulated learning skills. Conversely, low-achieving students may need guidance and support in the early stages to help them develop basic self-regulated learning skills.

5.5 Limitations and suggestions for future research

First, while this study explored the role of basic psychological needs in the development of self-regulated learning in online courses, it did not evaluate the extent to which these needs were fulfilled through the online learning environment and activities.. In other words, this study treated basic psychological needs as individual characteristics and did not examine how the online course environment satisfied these needs. Since basic psychological needs were shown to play a key role in the development of self-regulated learning, future research should investigate how their fulfillment in online learning environments impacts self-regulated learning development. Furthermore, future studies should investigate how online learning affects changes in basic psychological needs and whether changes in these needs and changes in self-regulated learning are interrelated.

Second, this study includes a limited set of variables related to developmental differences in self-regulated learning. It focused solely on academic achievement and basic psychological needs to explain differences in self-regulated learning development. However, self-regulated learning researchers suggest that changes in self-regulated learning may vary dynamically at different stages of learning. Future studies should consider environmental factors such as the characteristics of the online learning environment, learning activities, and the nature of the tasks to analyze the development of self-regulated learning from a more

diverse perspective. Additionally, further research should examine psychological factors, such as learning motivation and interest, which are known to significantly influence self-regulated learning (e.g., Kizilcec et al., 2017; Littlejohn et al., 2016) but were not addressed in this study. Moreover, this study did not explore differences in the development of self-regulated learning across school levels. Given that middle school students demonstrated higher initial levels of self-regulated learning compared to upper elementary school students, it is plausible that developmental differences may exist between school levels. Therefore, future research should explore these differences and the developmental trajectories of self-regulated learning across different educational stages.

Third, the present study is limited by utilizing a single measure of self-regulated learning and fails to account for the multiple dimensions of self-regulated learning. Self-regulated learning generally comprises cognitive, behavioral, and motivational components, and each component has different developmental trajectories (e.g., Mejeu & Held, 2022). Additionally, the relevance of basic psychological needs to the subcomponents of self-regulated learning differs (e.g., Hidayatullah & Csíkos, 2023). Therefore, a more thorough examination of the development of each dimension of self-regulated learning and their growth trajectories in relation to the satisfaction of basic psychological needs in online learning courses may provide specific implications for effectively supporting students' development of self-regulated learning.

6 Conclusion

This study confirmed the growth of learners' self-regulated learning in an online learning environment over a 12-week period. The pattern of growth in self-regulated learning varied across achievement group. The study also found that autonomy, competence, and relatedness influenced the initial level of self-regulated learning but did not significantly affect its growth over the course. Specifically, autonomy and competence were related to self-regulated learning growth in low- and intermediate-achieving students, while relatedness was significant for high-achieving students. These findings suggest that supporting students' self-regulated learning in online environments should be tailored to their level of achievement and psychological need satisfaction. Furthermore, as the degree of psychological need satisfaction is linked to the development of self-regulated learning, online learning environments and activities should be designed to fulfill students' basic psychological needs.

Appendix

Table 9 Self-regulated learning and basic psychological need satisfaction assessments

Self-regulated learning	<p>I plan how much time and effort to invest in studying</p> <p>I choose appropriate learning strategies depending on the situation</p> <p>I try to identify the problems that arise while I study</p> <p>I evaluate myself to see if I have achieved my study goals</p> <p>I adjust my study goals and plans based on current results</p> <p>I set my own study goals in advance</p> <p>I check to see if I am making progress towards my study goals</p> <p>When I need to study, I resist the temptation to play</p>
Autonomy	<p>I feel that others control me. (R)</p> <p>I don't have many opportunities to decide how to do my work. (R)</p> <p>In daily life, I often have to do what others tell me to do. (R)</p> <p>I feel that I can generally express my thoughts and opinions freely</p> <p>I feel that I can decide for myself how to live my life</p> <p>When doing something, I often follow others' ideas or ways of doing things rather than my own. (R)</p>
Competence	<p>I feel that I am very efficient (the results of my efforts are generally good)</p> <p>I feel a sense of pride in most of the things I do</p> <p>People who know me say that I do my work well</p> <p>I feel that I am capable of solving the tasks given to me</p> <p>I feel that I can teach others what I know</p> <p>I feel that I excel in many things compared to others</p>
Relatedness	<p>I feel loved and cared for by the people around me</p> <p>It seems that the people I meet frequently do not like me much. (R)</p> <p>I get along well with the people I meet</p> <p>I really like the people around me</p> <p>The people around me and I generally help each other</p> <p>The people around me often share their feelings with me</p>

Table 10 Mean differences and homogeneity variance tests across school levels

Variables	Mean (Standard Deviation)		t-test		Bartlett's test	
	<i>Elementary</i>	<i>Middle</i>	<i>t</i>	<i>p</i>	$\chi^2(df)$	<i>p</i>
1. Self-regulated learning_T1	5.00 (1.20)	5.23 (1.19)	-3.13	0.002	0.10(1)	0.754
2. Self-regulated learning_T2	5.31 (1.13)	5.59 (0.94)	-3.65	<0.001	13.35(1)	<0.001
3. Self-regulated learning_T3	5.46 (1.08)	5.53 (0.97)	-0.86	0.392	3.57(1)	0.059
4. Self-regulated learning_T4	5.43 (1.10)	5.63 (0.95)	-2.43	0.015	6.47(1)	0.011
5. Autonomy_T1	4.15 (0.63)	4.20 (0.63)	-1.36	0.174	0.03(1)	0.859
6. Competence_T1	4.88 (0.78)	4.83 (0.83)	1.12	0.261	2.02(1)	0.155
7. Relatedness_T1	4.97 (0.81)	4.87 (0.83)	1.98	0.048	0.48(1)	0.487
8. Achievement	66.78 (19.49)	67.30(20.87)	-0.41	0.682	2.42(1)	0.120

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Data availability The data that support the findings of this study are available from Global Institute for Talented Education, Korea Advanced Institute of Science and Technology, but restrictions apply to the availability of these data, which were used under licence for the current study and so are not publicly available. The data are, however, available from the authors upon reasonable request and with the permission of Global Institute for Talented Education.

Declarations

Conflict of interest The authors declare that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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