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ORIGINAL RESEARCH

Mine the process: investigating the cyclical nature of upper primary school students' self-regulated learning

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Abstract

The present study investigates primary school students' self-regulated learning (SRL) process by exploring the sequence in which SRL activities are conducted during learning. The aims of this study are twofold: investigating the presence of the theoretically hypothesized cyclical nature in students' SRL process, as well as potential differences herein for high, average, and low achievers. Think-aloud data of 104 upper primary school students were analysed by means of process mining analysis. The results indicate that students commonly adopt a cyclical approach to learning by implementing preparatory, performance, and appraisal activities during learning. However, the results indicate clear differences in the quality of students' SRL process. High achievers, compared to low and average achievers, show a more strategic and adaptive approach to learning during all phases of their learning process. They more strategically and effectively orient on and plan assignments, combine different cognitive strategies, and adopt self-evaluation to regulate their learning process.

Keywords Self-regulated learning · Primary education · Process mining · SRL processes · Achievement

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Introduction

In the 1980′s the concept of *self-regulated learning* (SRL) first appeared in the educational research literature (Dinsmore et al. 2008). Ever since, SRL received increasing attention in both research and practice due to its clear link with academic achievement and lifelong learning (e.g., Mega et al. 2014; Zimmerman 2008). In this respect, research indicates that high SRL learners have a more successful academic career and outperform their peers on standardized tests (Kistner et al. 2010; Mega et al. 2014; Paloş et al. 2011; Pintrich and De Groot 1990). More in particular, high achievers appear to regulate their learning process more effectively (Stoeger et al. 2015) by adopting SRL strategies more frequently (Cleary and Chen 2009; Heirweg et al. 2019; Vanderstoep et al. 1996), but also by implementing more deep-level strategies in challenging learning tasks and assignments (Malmberg et al. 2013). Furthermore, they report a more positive motivation (Heirweg et al. 2019; Vansteenkiste et al. 2009), as well as more positive emotions when learning (Pekrun et al. 2002).

Despite the insights in SRL and performance differences between students, the majority of SRL studies also resulted in a variety of applied theoretical perspectives and models on SRL (e.g., Boekaerts 1997; Pintrich 2004; Winne 2011; Zimmerman 2002). While these models often emphasis different components of SRL, large similarities are, however, present as well. In this respect, it is generally agreed upon that SRL entails a metacognitive, cognitive, and a motivational component (Dinsmore et al. 2008; Veenman et al. 2006; Zeidner et al. 2000; Zimmerman 2008). While the *metacognitive* component refers to higher-order thinking processes that permit the planning, monitoring, and evaluation of the learning process, the *cognitive* component includes learning strategies required for processing information, such as rehearsing, summarizing, paraphrasing, etc. (Winne and Perry 2000; Zimmerman 2000). Finally, the *motivational* component encompasses learners' motives for learning, their effort, and persistence, such as positive self-talk or making tasks more interesting (e.g., Boekaerts 1997; Pintrich 2004; Winne 2011; Zimmerman 2002).

Next to the accord on the multi-component character of SRL, the models in the literature also correspond as to their definition of SRL as a cyclical process, consisting of different phases. Although a different number of phases and divergent terminology is used across the different models, theorists agree that SRL encompasses different activities taking place before, during, and after learning, following a cyclical order, with the flexibility to repeat or return to prior phases. This agreement was explicitly acknowledged by Panadero (2017) in his analysis and comparison of six theoretical SRL models (i.e., Boekaerts and Corno 2005; Efklides 2011; Hadwin et al. 2011; Pintrich 2000; Winne and Hadwin 1998; Zimmerman 2000). In line with the prior work of Puustinen and Pulkkinen (2001), he concludes that the models generally share three similar phases: (1) a preparatory phase, (2) a performance phase, and (3) an appraisal phase. While the preparatory phase includes learning strategies conducted *before* the actual learning process (e.g., task orientation, interpretation, goal setting, planning), the performance phase refers to activities conducted *during* learning (e.g., cognitive processing, monitoring, control). Finally, the appraisal phase includes students' judgments and reactions *after* learning, such as their self-reactions (e.g., self-satisfaction, positive affect regarding their performance), performance feedback and self-evaluation. While these phases represent a general time-ordered sequence, they do not assume that specific activities should always occur before or after other kind of activities (Azevedo 2007; Pintrich 2000; Zimmerman 1986, 2000). As such, the models agree on the idea that learners should go through the phases adaptively, rather than linearly, on the basis of specific individual (e.g., prior knowledge, current level of understanding), task-related (e.g., level of challenge), and contextual (e.g., diversion, noise) characteristics.

Despite the recurrent attention attributed to the abovementioned phases of SRL in theoretical models and frameworks, the cyclical nature of SRL is rarely object of study in empirical research. This explicitly comes to the fore when taking a closer look at the dominant methodological approaches in previous SRL research. As to the data collection methods, off-line instruments (e.g., self-report questionnaires presented to the learner either before or after task execution) were almost exclusively administered for a long time (Panadero et al. 2016). However, these off-line instruments have several disadvantages. First, as they strongly rely on participants' self-assessment, they are valuable for mapping students' perception on their own learning, but consequently also vulnerable to socially desirable responses and to over- or underestimation. Second, they do not necessarily shed light on the actual self-regulating processes as they are not collected during learning (Merchie and Van Keer 2014a). In view of overcoming these critiques, a second wave of SRL research emerged, aiming to register learners' SRL activities during actual learning by adopting on-line data collection instruments, such as think-aloud protocols (Panadero et al. 2016). Especially applying think-aloud methodology to assess late primary school children's SRL has shown to be very suitable to gain a more objective and process-oriented perspective on SRL (e.g., Greene et al. 2011; Panadero et al. 2016; Vandevelde et al. 2015). These online data additionally have the advantage of enabling the investigation of the theoretically hypothesized cyclical nature of learners' SRL process, as these measures provide the opportunity of uncovering the sequence and the context in which SRL activities take place in addition to registering which and how often strategies are applied during learning. Unfortunately, however, to date this focus did not yet receive an explicit place in the current SRL studies. In this respect, it can be noted that the data analysis methods used in SRL research did not evolve simultaneously with the data collection approaches. In particular, when analysing on-line SRL data, researchers still primarily use a variable-oriented data analysis approach by reporting merely on the number and frequency of specific SRL activities learners show during learning (e.g., Scheiter et al. 2018; Taub et al. 2016; Vandevelde et al. 2015). Yet, the complex portraying of how and in which sequence these activities actually unfold and are combined throughout the complete learning process remains understudied. Consequently, empirically uncovering the cyclical nature of the SRL process stressed in the theoretical models remains unexplored. This is however important as the sequence and moment in which activities are conducted determines the quality of students' SRL process. In view of actually opening the black box of students' cyclical SRL behaviour during learning, more process-oriented approaches to both data collection and analysis are required to study the timing, contexts, and order in which students adopt SRL strategies in-depth. In this regard, process mining (Fluxicon 2019; Van der Aalst 2011) appears a promising analytical technique that enables researchers to visualise the course of students' actual learning based on time stamps, reflecting the moments wherein students conduct SRL activities. In doing so, it provides an overview of the sequence in which SRL activities were executed and the paths between these activities. The *activities* show which and how frequent different SRL strategies are adopted, whereas the *paths* visualize the sequence of activities and the frequency of each of these sequences (Fluxicon 2019; Van der Aalst 2011).

While process mining has already proved its value for analysing and optimizing business processes, it is only used to a very limited extent in the context of SRL (e.g., Bannert et al. 2014; Schoor and Bannert 2012). The first insights of these studies are promising, but further research remains nevertheless required for several reasons. First, due to the labour-intensive nature of analysing think-aloud protocols, prior research only included rather small samples of students. Therefore, upscaling is called for. Second, these studies provide a rather general and simplistic view on students' SRL process as only few SRL activities were included in the analysis. Third, prior studies exclusively involved university students in the specific context of computer-supported collaborative learning. This implies that information is lacking on younger learners and on learning in individual contexts without computers. Fourth, until now only the SRL process of high and low achievers was mapped and therefore recommendations for research on average performers were formulated (Bannert et al. 2014).

The present study

Taking into account the abovementioned considerations, guidelines and gaps in the current literature (see theoretical introduction), the present cross-sectional study investigates upper primary school students' actual use of SRL by means of online data collection through thinking aloud and by applying process mining. Contrary to the very limited existing research in this regard, the present study includes a rather large sample of upper primary school students ($n=104$) and investigates from a predominantly qualitative perspective low, average and high achievers' spontaneous use of SRL within an individual, non-computer supported learning setting. More specifically, we aim to confirm the theoretical assumption that SRL unfolds as a cyclical process, consisting of different recurrent phases (RO1) and to portray differences in the SRL process of high, average, and low achievers (RO2). As prior research indicates that more efficient SRL learners obtain higher achievement scores (e.g., Liu et al. 2014; Malmberg et al. 2010; Vauras et al. 1994), we hypothesize a more adaptive and cyclical use of SRL strategies in high achievers than in average or low achievers.

Method

Participants

The data of this study were collected in the context of a large-scale study ($n=2027$) (Heirweg et al. 2019) in which a sub-section of the participants was randomly selected to perform a think-aloud task. A total of 105 students from 41 different Flemish (Belgian) schools were selected from the larger sample with respecting gender balance and representing a cross section of abilities. In this respect, 52 (49.5%) girls and 53 (50.5%) boys, and respectively 33.3%, 34.3%, and 32.4% students with a generally low, average, and high ability level were selected.[1] Participating students had a mean age of 10.80 years with 50.5% fifth and 49.5% sixth graders. The majority of the students (93.3%) were native Dutch speakers, which is the language of instruction in Flanders. The protocol of the study was approved

[1] Since no national measures of academic standards are available in Flanders and in line with prior research (e.g., Merchie and Van Keer 2014b; Perry and VandeKamp 2000; Wijsman et al. 2016) teacher judgements on students' general ability level were used to select participants and assure a cross-section of abilities in the sample. In this respect, prior research indicates that using teacher judgements is a reliable technique to estimate students' ability level since their strong congruence with students' actual scores (e.g. Südkamp et al. 2012).

by the ethical committee of the Faculty of Psychology and Educational Sciences of Ghent University, Belgium. All participants and their parents agreed to participate in the TAPA administration by means of active informed consents.

Instruments

Think-aloud study task

A think-aloud study task consisting of two steps was administered. Following the recommendations of prior research (Greene et al. 2011; Someren et al. 1994), a 15-min training in thinking out loud was organised as a first step. During this step, students were asked to fold an origami swan while verbalizing all their thoughts and behaviour. Feedback was provided by the researcher on students' verbalisations in view of optimizing their thinking aloud. Second, students were instructed to think out loud during the execution of different assignments. While the primary aim of the present study was to investigate students' SRL activities during studying an informative text, students were also presented with other assignments in view of creating an authentic learning setting and providing opportunities to implement various SRL activities. More specifically, the assignments consisted of (1) an optional (i.e., not mandatory) "connect the dot" game, (2) five mental calculation exercises, (3) memorizing the translation of six French words, and (4) studying a 492-word informative text on seahorses. While the fourth assignment regarding studying the text was specifically developed to measure the task-specific use of cognitive (e.g., summarizing, highlighting, elaboration strategies), metacognitive (e.g., planning the text study approach), and motivational strategies (e.g., positive self-talk), the other assignments were included to also capture students' overall use of metacognition (e.g., planning the order of assignments, generally monitoring of time and progress, evaluating the completing) and motivational strategies (e.g., persistence) (see also Appendix Tables 2 and 3). However, the task-specific use of SRL strategies was not analysed for the first three assignments.

In view of encouraging students to plan their work, they were informed to have 50 min time for task completion. To enable students to monitor their progress, a clock was provided, but no further time indications were given to prevent prompted monitoring of time. Students were encouraged to approach assignments as they would normally do at home, using all materials they usually have at their disposal (e.g., dictionary, highlighting pens). During the task completion process, students were observed by the researcher and were only prompted to continue verbalizing when necessary (Greene et al. 2011). On average, students needed 25 min ($SD = 13.50$) to complete all tasks. While the fastest student completed the assignments in only 6 min, 9 students used the maximum available time of 50 min.

Cued recall test and achievement level grouping

About 15 min after the think-aloud procedure, students were asked to complete a cued recall test regarding the informative text and the French vocabulary. The test consisted of seven open questions that functioned as cues to support students' recall of information. All questions were corrected by means of a predefined answer key constructed by an expert panel, with more detailed responses resulting in higher test scores (see Appendix Table 5 for questions and a detailed answer key). As can be seen, the cued recall test entails questions from varying difficulty levels, querying information more literally stated in the text (i.e., question 1a, 3, 5, 7) but also questions requiring students to make inferences and transfer (i.e., question 1b, 2, 4, 6). In this way, and as advised in prior research (Fox 2009), the test went beyond only reproduction and assesses multiple levels of learning. Furthermore, also the use of this open-ended response format is advised in prior research, especially when trying to understand differences between achievement level groups (DiFrancesca et al. 2016).

The following decision process outlined below was undertaken to decide upon the grouping of students into high, average and low performers in this particular study context. In contrast with other research, where students are often grouped based on grade point averages (GPA) or scores on national or standardized tests (e.g., Nandagopal and Ericsson 2012), no such measures of academic standard are available in Flanders. In this case, often-used alternatives to decide upon students' achievement level are using (a) teacher judgements (e.g. Merchie and Van Keer 2014b; Perry and VandeKamp 2000; Wijsman et al. 2016) or (b) test scores on (non-standardized) performance tests (e.g., Bannert et al. 2014; DiFrancesca et al. 2016; Schoor and Bannert 2012). Related to the first alternative 'teacher judgements', the meta-analyses of Südkamp et al. (2012) indeed shows that these judgements can be used as reliable estimates of students' general ability level. Also, in our study, teacher judgements on students' general ability level were collected in view of balanced participant selection (see participants section). However, it was decided not to use these general judgements to group students into low, average and high achievers. It was opted for the second alternative (b) 'test score on a performance test' in view of the in-depth study of students' SRL processes. More particularly, due to this in-depth focus, relying on general teacher judgments to group students might be problematic. A very recent meta-analyses from Lawson et al. (2019) namely shows that many teachers have poor levels of knowledge about effective SRL strategies, and only assess students' SRL strategies to a limited extent (Lawson et al. 2019). Recent research confirms this, finding that even though teachers rate their students' SRL behavior on a moderate level, in practice, students only applied SRL strategies superficially. Furthermore, there was a large variability across students and tasks (Vandevelde et al. 2017). For this reason, teachers might not be able to accurately estimate students' self-regulatory abilities and related performance as being high, average or low. Therefore, it was decided to group students based on percentile rankings derived from their actual study performance (e.g., also following Bannert et al. 2014; DiFrancesca et al. 2016; Schoor and Bannert 2012). In this way, a direct and close connection is assured between students applied SRL processes and their subsequent performance, which is described as a strength in prior research (Nandagopal and Ericsson 2012).

More particularly, in view of relating students' SRL process to their achievement, students' cued recall scores were divided into 3 percentile ranks by means of SPSS 22. Overall, cued recall scores varied between 1 and 19.50 out of 20, with a mean score of 9.22. *Percentile 1* includes students with cued recall scores between 1 and 7.50, representing the 35 (33.7%) 'low achieving' students. *Percentile 2* contains the 37 (35.6%) students with scores between 7.75 and 11.25, while *percentile 3* includes the group of 'high' achieving students with test scores between 11.5 and 19.5 ($n=32$; 30.7%). In all further analysis, we will shortly refer to these groups as 'low', 'average' and 'high' achieving students.

Data analysis

Think aloud coding procedure and analysis

All think-aloud protocols were audio- and videotaped, resulting in 44 h and 10 min of data. Both students' verbal and non-verbal behaviour (e.g., highlighting) was transcribed by means of a computer program for subtitling videos (i.e., Subtitle Workshop 4). This approach permits to register the start and end time of each verbalisation and action, which is essential in view of conducting process mining as the sequence of activities is calculated on the basis of their exact time frame.

Think-aloud protocols were analysed qualitatively by means of a coding scheme (see further). First, the protocols were segmented into different units for analysis purpose. More particularly, it was opted to use ‘units of meaning’. Here, one unit refers to a thematically consisted verbalization of a single self-regulatory activity (Chi 1997; van Someren et al. 1994). For instance, when students articulated ‘I will first read the text, then underline keywords and try to memorise the text’ it was coded with the self-regulatory activity ‘planning’. In Appendix Tables 2 and 3 more examples of units of meaning and their corresponding coding category are represented. In Appendix Table 4 an excerpt from a think-aloud transcript and the associated coding for different units of meaning can be found. Repeated actions (e.g., students repeatedly highlighting key words) were analysed as separate activities and not as one single segment in view of considering the recurrence of different SRL strategies. In this way students who used particular strategies more intensively could be distinguished (Vandevelde et al. 2015). This resulted in a total of 5.917 units that were coded by means of a coding scheme based on prior research of Vandevelde et al. (2015).

The coding scheme consists of 18 subcategories referring to the cognitive, metacognitive, and motivational component of SRL (see Appendix Tables 2 and 3). More specifically, students’ use of metacognitive and motivational SRL activities were analysed by means of 10 categories (see Appendix Table 2) that were coded respectively for the study text, as well as for the other assignments (i.e., game, mathematics, French). Separately coding these strategies both for the assignment of studying the informative text and also for the other assignments enabled us to map students’ task orientation, planning, etc. in the task-specific context of studying the text, as well as when facing the other tasks. Furthermore, students’ cognitive strategy use during text studying was additionally and more in detail analysed by means of 8 coding categories (see Appendix Table 3).

In view of checking interrater reliability, 23.08% of the think- aloud protocols ($n=24$) were double-coded by two independent trained coders, resulting in a high agreement with Krippendorf’s $\alpha=0.89$.

In a first stage, descriptive quantitative analyses were performed on the occurrence of the displayed strategies. In a second stage, in-depth qualitative analyses were performed by means of process mining analysis (see below).

Process mining analysis

The qualitative process mining analysis was conducted using Disco (Fluxicon). The Disco software enables researchers to obtain insight in complex processes by creating visual maps. In the context of SRL, this process map more particularly displays two elements: (1) all *activities* performed by the participants before, during, and after learning (i.e., the boxes is Figs. 1, 2, 3 and 4) and (2) all connections or *paths* between these activities (i.e., the arrows in Figs. 1, 2, 3 and 4), illustrating the sequence in which activities were conducted. Both unidirectional paths, bidirectional paths, and loops are depicted, indicating that activities were respectively conducted in consecution (unidirectional path), in alternation (bidirectional path), or that one activity was performed several times in succession (loops).

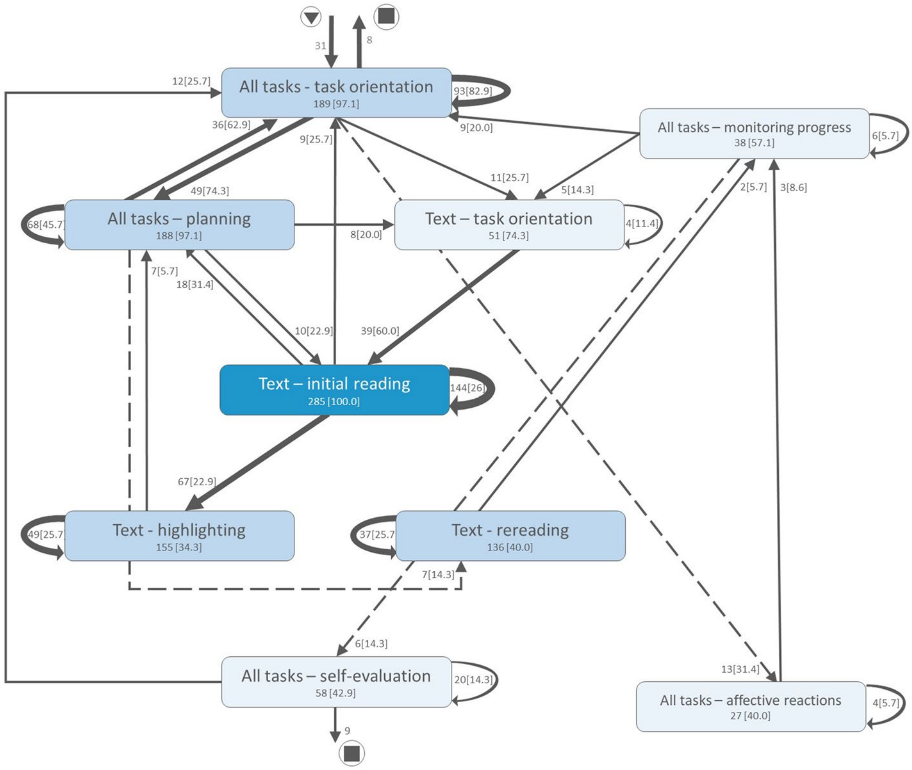

Fig. 1 Overview of all learners' SRL processes ($n = 104$). The boxes present the different activities, while the arrows refer to the paths or the sequence in which activities were conducted

In addition to presenting visual maps, Disco enables researchers to enhance interpretability of the multitude of combinations between *activities* and *paths* by synthesizing the number of both these elements included in the process map. In this regard, as to the activities, the researcher can explore from 1 to 100% of the activities in the visualisation, ranging from displaying only the most frequent SRL activities up to all activities that ever occurred in the data set. Similarly, as to the paths, only the most dominant *paths* can be selected, but also very seldom occurring paths can be included. By selecting a specific percentage of *activities* and *paths* (e.g., 50%), Disco automatically calculates which activities should be included in or excluded from the process map on the basis of the *fuzzy miner* algorithm. Even though the word "fuzzy" insinuates the opposite, this algorithm permits to analyse very complex and highly unstructured processes (Van der Aalst 2011) such as, for example, SRL. In particular, it relies on two metrics, *significance* and *correlation*, to decide which activities and paths should be retained in the process models (Günther and van der Aalst 2007). *Significance* refers to the relative importance of activities and paths, implying that, for example, more frequent elements are retained in the model. *Correlation*, on the other hand, is deployed for selecting only paths of closely connected activities (Günther and van der Aalst 2007). As a result, SRL strategies that are often conducted by a large group of students will be included, while less frequent activities or activities that are repeatedly conducted by only few students will be excluded from the process map (see discussion section for more information).

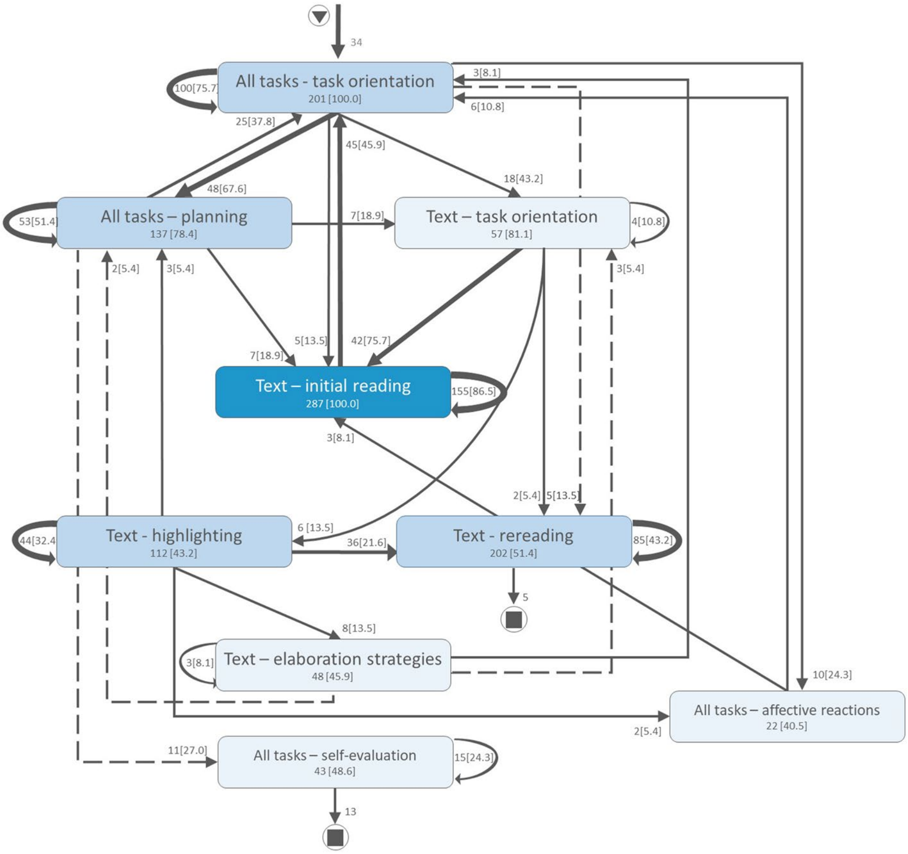

Fig. 2 The SRL process of low achieving students ($n=35$) with the respective frequencies of occurrence and, between brackets, the percentage of students that conducted the activity at least once

The *fuzzy miner* algorithm is applied in the present study in analogy with prior research in the field of SRL (Bannert et al 2014; Schoor and Bannert 2012). However, in the present study a different software (i.e., Disco instead of ProM) is used to visualize the sequence in students' activities. While the underlying principals are comparable, we opt for the use of Disco for two reasons. First, it enables analysing very large and complex data sets. Second, it is known to be very accessible and intuitive to use (Van der Aalst 2011).

The decision on the percentage of activities and paths to be included in the analyses largely depend on the complexity of the investigated process (Fluxicon 2019). At present, however, no specific guidelines are available in this particular educational research context. In general, researchers are recommended to include as much activities and paths as possible, while avoiding too complex process maps (Fluxicon 2019). In the particular context of the current study, this general guideline was followed, and the percentages of included activities and paths were carefully deliberated among the authors of this manuscript, who all are strongly affiliated with the SRL research literature. In a first exploration phase, all activities and paths were displayed. This resulted in an extremely large, complex, and difficult to interpret map. In a following phase, the percentage of displayed activities and paths was therefore systematically decreased. This procedure was stopped when it resulted in the

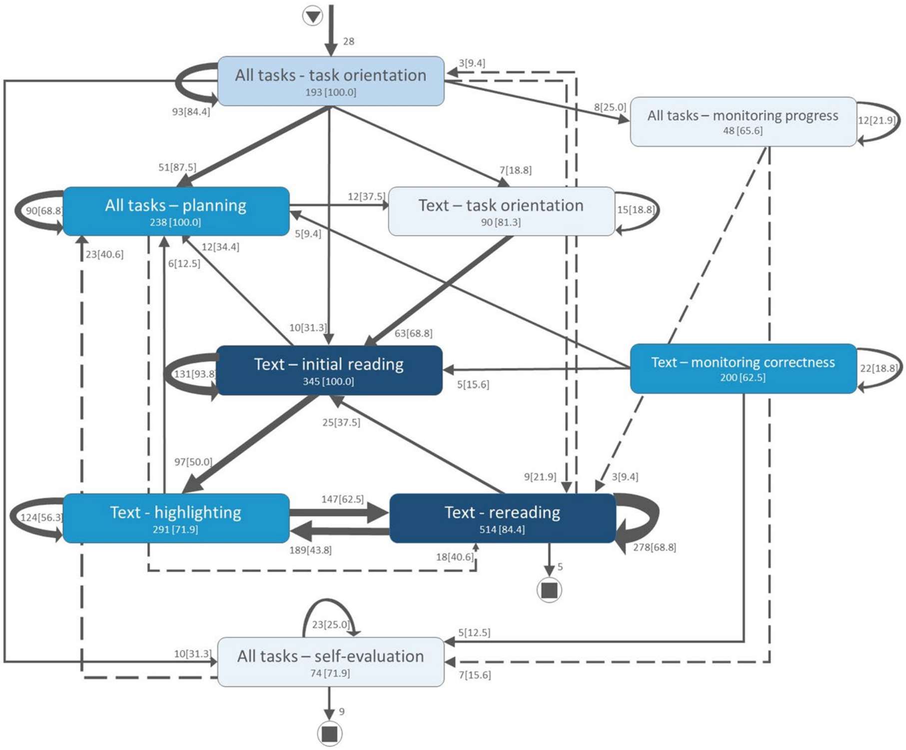

Fig. 3 The SRL process of average achieving students ($n=37$) with the respective frequencies of occurrence and, between brackets, the percentage of students that conducted the activity at least once

disappearance of important SRL activities or paths. As a result, the 33.3% most frequent SRL activities and the 33.3% most frequent connections between these activities were included in the analysis.

A process map including all learners ($n=104$) was used in view of presenting the results of RO1, while three process maps with respectively low ($n=35$), average ($n=37$), and high achievers ($n=32$) were analysed and presented in view of RO2.

Results

Descriptive results: frequency of occurrence of SRL activities in different achievement groups

Table 1 presents the absolute frequency of occurrence of all SRL activities observed during thinking aloud. Activities highlighted in grey are included process maps of respectively all learners (RO1), and of the low, average, and high achievers in specific (RO2) when selecting 33.3% of all activities and paths.

As to the SRL activities included in the process maps, the absolute frequency of occurrence indicates that high achievers ($n=32$) generally perform more SRL activities than

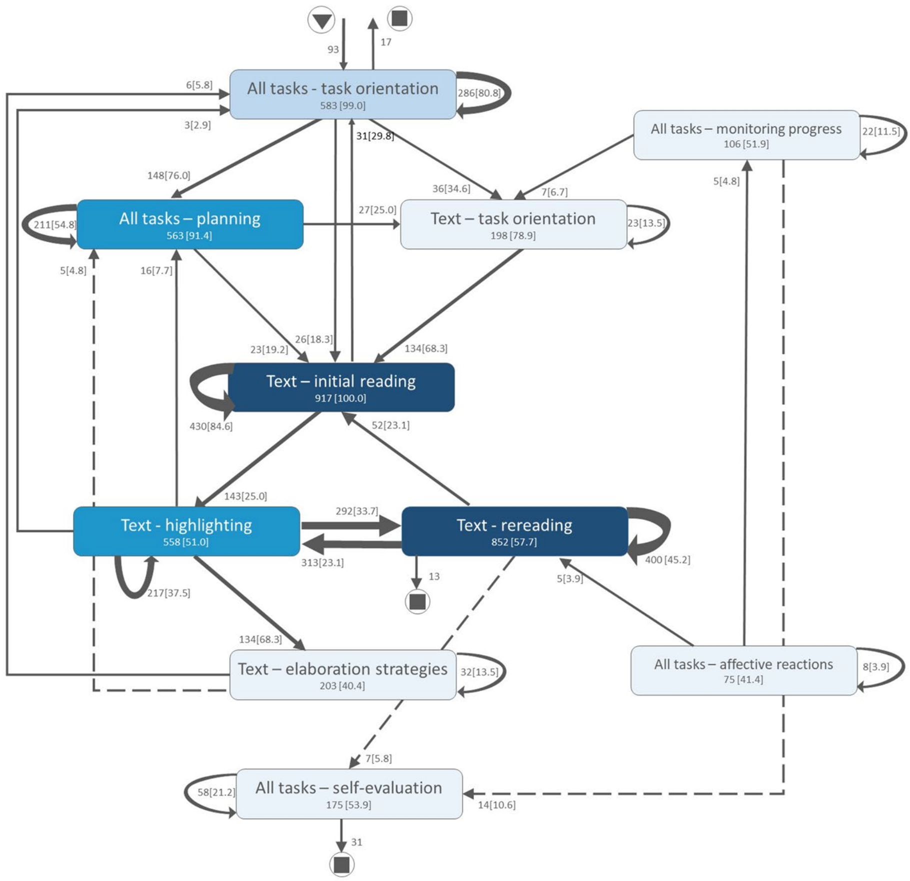

Fig. 4 The SRL process of high achieving students ($n=32$) with the respective frequencies of occurrence and, between brackets, the percentage of students that conducted the activity at least once

average ($n=37$) and low achievers ($n=35$), except for task orientation and affective reactions during all tasks. While high achievers also show a noticeable higher use of elaboration strategies than low or average achievers, these strategies are nevertheless only included in the average achievers' process map. This is the case since for the group of high achievers, the elaboration strategies do not belong to the 33.3% most frequently occurring activities conducted by a large group of students.[2]

As to the SRL activities that are not included in the process maps, differences between the achievement groups are consistent with these findings. The results moreover indicate that students most frequently adopt memorizing and summarizing strategies. It should however be noted that these strategies are predominantly and extensively used by a rather small share of high achievers, while only few low and average achievers memorize or summarize the study text. With regard to students' monitoring, the most common type of monitoring concerns the strategic approach monitoring when studying the informative text. Additionally, a small share of low, average, and high achievers conducts comprehension monitoring

[2] Note that elaboration strategies are conducted by only 18 of the 32 high achieving students, while the SRL activities included in high achievers' process map are adopted by 20 or more students.

Table 1 Frequency of occurrence of SRL strategies for respectively all achievers and per each achievement group

	All learners ($n=104$)		Low achievers ($n=35$)		Average achievers ($n=37$)		High achievers ($n=32$)	
	Absolute freq	*N* students[a]	Absolute freq	*N* students[a]	Absolute freq	*N* students[a]	Absolute freq	*N* students[a]
All tasks								
Task orientation	*583*	*103*	*189*	*34*	*201*	*37*	*193*	*32*
Planning	*563*	*95*	*188*	*34*	*137*	*29*	*238*	*32*
Monitoring								
Approach	2	1	0	0	2	1	0	0
Insight: confusion	59	28	9	7	25	12	25	9
Insight: understanding	47	23	14	7	23	10	10	6
Progress	*106*	*45*	*38*	*20*	20	13	*48*	*21*
Correctness	8	5	4	1	1	1	3	3
Self-evaluation	*175*	*56*	*58*	*15*	*43*	*18*	*74*	*23*
Motivation	14	4	12	2	0	0	2	2
Affective reactions	*75*	*43*	*27*	*14*	*22*	*15*	26	14
Text								
Task orientation	*198*	*82*	*51*	*26*	*57*	*30*	*90*	*26*
Planning	17	14	5	4	3	3	9	7
Initial reading	*917*	*104*	*285*	*35*	*287*	*37*	*345*	*32*
Highlighting	*558*	*51*	*155*	*12*	*112*	*16*	*291*	*23*
Rereading	*852*	*60*	*136*	*14*	*202*	*19*	*514*	*27*
Elaboration strategies	*203*	*42*	32	7	*48*	*17*	123	18
Memorising	0	0						
Knowledge telling	240	29	15	4	43	10	182	15
Knowledge transforming	284	21	24	3	34	8	226	10
Summarizing	0	0						
Structured	338	19	94	4	73	7	171	8
Non-structured	103	12	1	1	29	4	73	7

Table 1 (continued)

	All learners (n = 104)		Low achievers (n = 35)		Average achievers (n = 37)		High achievers (n = 32)	
	Absolute freq	*N* students[a]	Absolute freq	*N* students[a]	Absolute freq	*N* students[a]	Absolute freq	*N* students[a]
Monitoring	0	0						
Approach	107	31	24	9	33	10	50	12
Insight: confusion	54	22	2	2	26	12	26	8
Insight: understanding	40	17	1	1	18	10	21	6
Progress	84	33	16	8	23	11	45	14
Correctness	250	35	21	5	29	10	*200*	*20*
Self-evaluation	8	5	1	1	3	1	4	3
Motivation	13	9	1	1	7	5	5	3
Affective reactions	19	12	4	2	6	4	9	6

Activities highlighted in italics are included in the process maps when selecting 33.3% of all activities and paths

[a]Number of students conducting the strategy at least once

across all assignments, as well as in the context of the study text. This illustrates that some students monitor their understanding of the task assignment when confronted with different tasks, as well as their understanding of the text content when studying. Finally, the results show a low frequency of occurrence for students' verbalization of motivation in all task contexts, as well few utterances regarding students' self-efficacy and affective reactions in the context of the informative text.

RO1: exploring the theoretical assumption that SRL unfolds as a cyclical process consisting of different phases

In the context of RO1, the descriptive results were first inspected to verify whether SRL activities that can occur during the preparatory (i.e., task orientation, planning), performance (i.e., rereading, highlighting), and appraisal phase (i.e., self-evaluation) of students' learning were present in the process map. The results presented in Table 1 indeed confirm that SRL activities belonging to each of these phases are present in the process maps of all learners.

Second, the presence of a cyclical nature in the SRL process was analysed by examining the process map of all learners. In Fig. 1, the boxes represent different SRL activities. The arrows between the boxes (i.e., activities) refer to the paths or the sequence in which the activities have been conducted.[3] When interpreting Fig. 1, two aspects are important to be correctly oriented on the map, that is (a) the general position of the boxes (i.e., SRL activities), being either at the top, centre, bottom and (b) the direction of the arrows. As to the general position of the boxes, activities that are primarily assumed to take place during the preparatory phase are represented at the top of the figure (i.e., task orientation and planning regarding all assignments, task orientation on the informative text; Pintrich 2004; Zimmerman 2002). In the centre of the figure, activities are represented that are generally expected during the performance phase (i.e., text-initial reading, highlighting, rereading, elaboration). At the bottom of the figure, activities are represented generally expected during the appraisal phase (i.e., self-evaluation). Second, as to the direction of the arrows, it can be seen in Fig. 1 that most arrows point from top to bottom, which implies that students indeed generally follow this *before—during—after* structure throughout their learning process. However, also loops and recurrent arrows, pointing from the bottom to the top are present, indicating that learners also repeat activities (e.g., task orientation or text-highlighting) or return to prior activities or phases throughout the process (e.g., from initial reading to planning). In this respect, the results illustrate that learners do not follow a strictly linear, but rather an adaptive and cyclical approach during learning.

RO2: exploring differences in the SRL process of high, average and low achievers

Figures 2, 3 and 4 illustrate respectively the process map of low, average and high achieving students on the SRL study task.

First, similar with Fig. 1, when overviewing the general position of the boxes (i.e. SRL activities), Figs. 2, 3 and 4 indicate that all students, regardless of their task-specific SRL achievement level, alternate activities from the *preparatory* phase (i.e., task orientation, planning) with activities from the *performance* phase (i.e., initial reading, highlighting,

[3] Solid and dashed lines do not represent substantive differences. They are included to enhance the figures' readability.

rereading). Additionally, it must be noted that some process maps include more boxes (i.e., SRL activities). For instance, text-elaboration strategies are included in the process map of average achieving students (Fig. 3), which is not the case in the map of low and high achieving students (Figs. 2 and 4). In this respect, we want to refer to our specific data analysis process and decision only to include the 33.3% most occurring activities and paths (see section 'process mining analyses').

Second, when overviewing the arrows, two prominent differences between low, average and high achieving students of different achievement levels come to the fore as well. First, it appears that only high achievers strongly alternate cognitive strategies during actual learning. More particularly, high achievers alternately engage in initial reading, highlighting, and rereading. This is shown in Fig. 4 in the arrows connecting the different cognitive strategies initial reading, highlighting, and rereading, and the presence of reciprocal arrows between them. These patterns are not so clearly present in low and average achievers' process maps. Second, deploying self-evaluation strategies appears different depending on students' achievement levels, as shown in the figure when focussing on the number of arrows—representing relationships—coming in and out 'self-evaluation' in Figs. 2, 3 and 4. While self-evaluation of high achievers appears to be strongly interconnected with other SRL strategies such as task orientation, planning and monitoring, this is a more freestanding activity in both low and average achievers' learning process.

In addition to these prominent differences, more fine-grained dissimilarities in students' preparatory, performance, and appraisal phase are revealed. First, differences in respectively students' preparatory, performance, and appraisal phase will be discussed. In view of improving clarity, differences in students' monitoring and affective reactions will be addressed separately as results of the present study indicate that these strategies are strongly intertwined with different preparation, performance and appraisal phase activities. These are elaborated on underneath.

Preparatory phase

As already mentioned, executed SRL strategies during preparatory phase are positioned at the top of the figures. As can be seen at the top of Figs. 2, 3 and 4, the SRL process of the majority of the students begins with task orientation regarding the different assignments (i.e., game, mathematics, French, study text). Regardless of students' achievement level, this is mainly followed by planning activities across all assignments (74.3%, 67.6%, 87.5% low, average and high achievers respectively) or by task orientation towards studying the informative text in particular (25.7%, 43.2%, 18.8% low, average and high achievers respectively). For high achievers, the unidirectional arrow from task orientation across all tasks indicates that this overall task orientation precedes the planning of all assignments. On the contrary, the bi-directional arrow in both low and average achievers' maps indicate the alternation of overall task orientation and planning activities.

As to studying the informative text, in particular, the results show that the majority of the students across achievement groups (74.3 to 81.3%) engage in task orientation. However, differences are present with regard to the moment in which task orientation is conducted. High achievers more often conduct task orientation on the study text immediately after planning all tasks (37.5%) than low (20.0%) and average achievers (18.9%) (cf. unidirectional arrow from 'all-task—planning' to 'text- task orientation' in Figs. 2, 3 and 4). The arrow from planning all tasks to initial reading in the maps of both low and average achievers, on the other hand, indicate that about a fifth of these learners (respectively

22.9% and 18.9%) immediately start reading the text after general planning, without engaging in task orientation on the study text first.

After initial text reading, both low and high achievers engage in (intermediate) planning activities (cf. unidirectional arrow from ‘text-initial reading’ to ‘all tasks-planning’ in Figs. 2 and 4), while low (25.7%) and average achievers (45.9%) sometimes conduct re(orientation) towards all tasks (cf. unidirectional arrow from ‘text-initial reading’ to ‘all tasks-task orientation’ in Figs. 2 and 3).

Performance phase

Concerning the cognitive strategies conducted during actual text studying (i.e., performance phase), represented in the centres of Figs. 2, 3 and 4, large similarities are present between achievement groups as to the most frequent activities (i.e., the activities included in the process maps.). In all groups, overall students appear to engage predominantly in initial reading (100% of all students), rereading of the text (40%, 51.4%, and 84.4% low, average and high achiever respectively) and in highlighting information (34.3%, 43.2%, 71.9% low, average and high achiever respectively). As already mentioned above and can be seen in Fig. 2, elaboration strategies are only present in the process map of the average achievers (see also section ‘process mining analyses’).

Notwithstanding the similarities, the results point out differences as well. As the percentages mentioned above show, high achievers strongly differ from low and average achievers as to their use of highlighting, and rereading strategies. More specially, the frequency of occurrence of these strategies is higher, as well as the percentage of students adopting the strategies at least once. In addition, also the unfolding of the process, displayed by the arrows in the maps, strongly differs. The unidirectional arrow from initial reading to highlighting in the group of high achievers reflects a consecutive conduction of these activities. Furthermore, in this group of students a clear bi-directional path is present between highlighting and rereading, implying that high achievers often perform these activities in alternation. These bi-directional arrows between highlighting and reading are missing in the process map of low and average achievers (i.e., Figs. 2 and 3).

When compared to high achievers (50%) only 22.9% of low achievers precede highlighting by initial reading (cf. unidirectional arrow from ‘text-initial reading’ to ‘highlighting’). However, their rereading activities appear not to be (reciprocally) connected to any other cognitive strategies (e.g., highlighting). For the average achievers, the process map shows no arrow between initial reading and highlighting, implying that these activities are not (often) conducted consecutively in this group of students. Highlighting, however, does precede rereading of (parts of) the text, but in contrast to high achievers, and as can be seen in Fig. 3, no bi-directional path was found.

As to elaboration strategies used by average achievers, it appears that these activities are mostly conducted after highlighting or before task (re)orientation towards all assignments or towards the study text in particular, or before the interim planning of all tasks.

As to the connection between activities in the preparatory and performance phase (cf. activities represented at the top and centre of the process maps), a bidirectional arrow between task orientation on all tasks and rereading is present in the high achievers’ map. This indicates that some high achievers (9.3 to 21.9%) reorient on the different assignments before and after rereading the text. While this path is not present in the low achievers’ map (Fig. 3), a small share of average achievers performs task orientation on respectively all tasks (13.5%) and the text (5.4%) before rereading (cf. unidirectional arrows from ‘all tasks-task orientation' and 'text-task orientation' to 'text rereading'), as well as task orientation on the text before highlighting (13.5%) (cf. unidirectional curved arrow from 'text-task orientation' to 'text-highlighting').

As to the relation between rereading, highlighting and planning all assignments, large similarities are present between achievement groups. Yet, low, average, and high achievers engage in (re-) planning activities after highlighting in the study text (cf. unidirectional arrow from 'text-highlighting' to 'all task-planning) in Figs. 2, 3 and 4, while low and high achievers also conduct (intermediate) planning after rereading (respectively 14.3 and 40.6%) (cf. unidirectional arrow from 'rereading' to 'all-task planning' in Figs. 2 and 4).

Appraisal phase

With regard to the activities executed in the self-reflection phase, represented at the bottom of Figs. 2, 3 and 4, only students' self-evaluation is included in the process maps as a frequently occurring activity. The results more particularly reveal that self-evaluation is not strongly connected to the other activities for both low and average achievers, which is shown by the lower numbers of in- and outcoming arrows in Figs. 2 and 3. In the high achievers' group, on the contrary, different arrows from and towards self-evaluation show the interrelatedness with students' task orientation, planning of all assignments, their overall monitoring of progress and their monitoring of text correctness. When considering the arrows from or towards self-evaluation, more in particular, the results indicate that low achievers (re)orient towards all tasks after evaluating their learning process (25.7%, Fig. 2), while high achievers first (re)orient on all task assignments before engaging in self-evaluation (31.3%, Fig. 4). Similarly, average achievers first (re)consider planning before self-evaluating (27%, Fig. 3), while high achievers first conduct self-evaluation before (re)considering the planning of all tasks (40.6%, Fig. 4).

At last, the arrows leading to the stop symbol in the process map show which activities were conducted as final SRL activity by the learners. The low frequency of occurrence connected to these arrows indicate that students end their learning process in diverse ways. The most frequent final activity is, for all achievement groups, self-evaluation, but also rereading or task orientation occur as final activities.

Monitoring and affective reactions across phases

As to students' monitoring and affective reactions, represented at the right sides of Figs. 2, 3 and 4, the process maps clearly show that these strategies are used very differently by all achievement groups. In particular, the results show strong differences in the activities that precede or follow students' monitoring and affective reactions.

For the high achievers (Fig. 4), the monitoring of progress during all tasks and the monitoring of correctness during studying the text are included in the process map. The unidirectional arrow from task orientation to the monitoring of progress indicates that these activities are conducted consecutively. Second, for 9.4% of the high achievers monitoring of progress is followed by rereading and for 15.6% by self-evaluation activities (cf. unidirectional paths from 'all tasks—monitoring progress' to these SRL strategies respectively). Monitoring of correctness is followed by initial reading (15.6%), planning across tasks (9.4%), and self-evaluation (12.5%) (cf. unidirectional paths from 'text-monitoring correctness' to these SRL strategies respectively).

In the average achievers' process map, only affective reactions appear to be present. Moreover, these affective reactions seem strongly interrelated with different types of SRL activities. As Fig. 3 illustrates, task orientation across tasks and highlighting activities during text learning seem to elicit affective statements, showed by the incoming arrows from these SRL strategies to affective reactions. These affective reactions are in turn followed by initial text reading (8.1% of the low achievers) and further task orientation across tasks (10.9% of the low achievers) (cf. unidirectional arrows from 'text-initial reading' and 'all task-orientation' to 'all-task affective reactions').

Finally, the low achievers' process map (Fig. 2) includes both monitoring of progress and affective reactions. Low achievers' monitoring of progress seems strongly interwoven with other SRL strategies as shown by the number of in- and outcoming arrows. This specific SRL strategy is preceded by affective reactions for 8.6% of the low achievers and rereading for 5.7% of the low achievers; and followed by task orientation across tasks (20%), task orientation on the study text (14.3%), and self-evaluation (14.3%) (cf. unidirectional arrows from these SRL strategies respectively to 'monitoring progress'). Low achieving students' affective reactions, on the other hand, appear to be preceded for 31.4% of the students by general task orientation and to be followed by progress monitoring for 8.6% of the students.

Discussion

Notwithstanding the multitude of studies on self-regulated learning (SRL), to date, little is known about the actual process and the different phases learners go through when implementing SRL (Klug et al. 2011). Therefore, the present study explores the presence of the theoretically hypothesized cyclical nature of SRL by mapping the sequence of occurrence of learners' SRL activities. Furthermore, differences in low, average, and high achievers' SRL process during thinking aloud is analysed by means of process mining.

While different theoretical frameworks exist on SRL (Boekaerts and Corno 2005; Efklides 2011; Hadwin et al. 2011; Pintrich 2000; Winne and Hadwin 1998; Zimmerman 2000), researchers generally agree that learners should conduct different SRL activities before, during, and after actual learning (e.g., Boekaerts and Corno 2005; Pintrich 2000, 2004; Zimmerman 2002), reflected in a preparatory, performance, and appraisal phase. The results of the current study substantiate this idea as these phases can generally be recognized in the process maps of all learners. However, theorists also underline that this sequence should not be followed linearly, but that an adaptive cyclical approach to learning is crucial (Panadero 2017; Pintrich 2000, 2004; Zimmerman 2002). The present results indicate that learners indeed implement a rather flexible, adaptive approach to learning as they often seem to repeat or return to prior SRL activities or phases. Notwithstanding the confirmative results regarding the cyclical nature of SRL, large differences occur in the quality of students' SRL process depending on their task-specific SRL achievement level. Five major findings come to the fore in this respect.

First, the present study confirms earlier research stating that high achievers more frequently adopt SRL strategies than low or average achievers (Heirweg et al. 2019; Cleary and Chen 2009; Vanderstoep et al. 1996), as descriptive results show a higher frequency of occurrence for all strategies, except for task orientation and affective reactions. High achievers thus clearly outperform low and average achievers as to the quantity of the applied SRL strategies.

Second, with regard to the SRL activities conducted as part of a preparatory phase, the results indicate a more recursive and alternate use of task orientation, planning, and initial reading in low and average achievers as compared to high achievers. As the presence of these alternations could reflect a cyclical and effective approach to learning, this would be a surprising result considering these students' low to moderate task performance for prior research indicated that a strategic, flexible and adaptive use of SRL strategies is related to higher achievement scores (e.g., Liu et al. 2014; Malmberg et al. 2010; Vauras et al. 1994). Within the present study, we however hypothesize that the found sequences and alternations in low and average achievers are rather indicators of a less efficient, less well-thought and consequently less desirable SRL process for two reasons. First, the strong alternation between overall task orientation and planning of all assignments and initial reading of the study text seems to point at the fact that low and average achievers often limit their actual studying to only initial and consequently one-time reading. After initial reading they appear to proceed to further orientation towards and planning of the other assignments. This hypothesis is supported by the descriptive results as well. More particularly, only half of the low and average achievers perform any rereading strategies, while almost 85% of the high achievers reread the text or specific paragraphs. Second, the present results seem to imply that low and average achievers more often start reading and studying without a thorough understanding of the task properties, leading to the need for reorientation towards or re-planning of the tasks. Quite the reverse, in line with prior research of Malmberg et al. (2013), we hypothesize that the absence of this alternation in high achievers indicates a more efficient and systematic study approach, where task orientation and planning precede actual learning.

A third important finding relates to the fact that the achievement-level differences in the systematic and/or cyclical approach of the assignments mentioned above, is reflected in students' cognitive strategy use during actual text learning as well. More particularly, low achievers often appear to combine highlighting simultaneously with initial reading, while high achievers more frequently alternate both strategies. The latter implies that high achievers first read a text fragment or text paragraph, highlight main ideas and then continue with the next paragraph. This difference in processing approach might indicate that high achievers adopt a more strategic approach to text studying than low or average achievers (Meneghetti et al. 2007; Merchie and Van Keer 2014b). Rather than immediately selecting and highlighting important ideas, they read text fragments, deliberate on the importance of the given information and then highlight the main ideas (Meneghetti et al. 2007). Yet, in these students, the cyclical nature of SRL is thus also reflected in their alternation of activities within one phase (i.e., rereading—highlighting—rereading) and not only in the alternation between different phases (e.g., planning—rereading—planning).

A similar difference can be found as to students' use of rereading strategies. In the low and average achievers' process maps, rereading appears to be a rather isolated phenomenon, not really connected to other cognitive strategies. In this respect, it can be supposed that low and average achievers use rereading as a rather surface-level rehearsal strategy, whereas high achievers seem to deliberately use rereading at a more deeper level to improve their initial text understanding or to select and highlight main ideas (Meneghetti et al. 2007; Merchie and Van Keer 2014b). When high achievers adopt rereading in view of rehearsing or further processing, this seems to be more deliberately planned than in the other achievement groups. This is illustrated by the fact that high achievers more frequently precede rereading by planning of all assignments, suggesting that they deliberately decide to reread the text after considering their progress and planning (e.g., realizing that they have finished the other assignments, that the informative text is the most important task).

Still regarding to the cognitive strategies, it seems surprising that elaboration strategies are only included in the average achievers' process map, while prior research indicates a positive relation between students' elaboration and their achievement scores (Eveland and Dunwoody 2000). When considering the descriptive results, however, it becomes evident that high achievers do engage in the application of elaboration strategies and even outperform average achievers as to the frequency of elaboration strategies. The absence of these strategies in the high achievers' process map is consequently only due to the fact that this activity does not belong to the 33.3% most frequent activities conducted by a large group of high achievers.

A fourth notable difference in students' SRL process regards their self-evaluation after actual learning. While in low and average achievers' process maps self-evaluation is rather isolated from the other SRL activities, it is clearly more strongly interwoven in the high achievers' map. Notwithstanding the fact that self-evaluation is performed equally often by all achievement groups, this finding implies that no real recurring pattern could be found as to low and average achievers' self-evaluation. In this respect, in these learners, self-evaluation is consequently rather randomly and uniquely applied before and after a wide variety of SRL activities. In contrast, a recurrent pattern is present in the group of high achievers, suggesting that they adopt self-evaluation more purposefully before (e.g., planning all tasks) and after (e.g., task orientation all tasks) specific SRL strategies as a form of interim checking. This more cyclical use of self-evaluation could imply that these learners more actively evaluate their learning in view of adjusting their planning, goals and choice of strategies, which is an indicator of effective self-regulating behavior (Schunk and Zimmerman 1998).

The fifth prominent finding of the current study regards students' use of monitoring and affective reactions. The results indicate that students' monitoring and affective reactions are strongly intertwined with different preparatory, performance, and appraisal phase activities. At first sight, this is surprising, as most theoretical frameworks place monitoring in the performance phase of the learning process (Hadwin et al. 2011; Pintrich 2000; Zimmerman 2000), while affective reactions are linked to the appraisal phase (Pintrich 2000; Zimmerman 2000). However, when taking a closer look at the theories, Pintrich (2000, 2004), for example, also explicitly states that that "monitoring, control and reaction can be ongoing simultaneously and dynamically as the individual progresses through the task" (Pintrich 2000, p. 455). The results of the current study consequently substantiate this idea, as low, average, and high achievers seem to track and control their progress, the correctness of their learning, as well as their feelings regarding the learning process throughout all phases of the SRL cycle.

Suggestions for future research

The results of this study show that process mining entails many opportunities for future SRL research. Considering the current trend toward more on-line measurement instruments, such as eye tracking and sensory data (e.g., Malmberg et al. 2013; Panadero et al. 2016; Scheiter et al. 2018; Taub et al. 2016), process mining provides opportunities to analyse this online data without reverting to the commonly used frequency analysis. Unfortunately, to date, the application of process mining in the field of social sciences is still in its infancy and clear analytical guidelines are lacking. This urges researchers to make rather difficult and sometimes arbitrary choices. From this point of view, we want to call for future research experimenting with process mining in view of sharing good practices and developing and improving process mining guidelines.

In this regard, future research investigating SRL both from a broader and a fine-grained perspective is recommended. As demonstrated in the present study, process mining permits researchers to obtain a general overview of students' SRL process. However, also more fine-grained analyses are feasible by, for example, exploring the sequence in which cognitive strategies are applied in various learning contexts. In this regard and in view of obtaining valid results, we believe it is crucial that researchers clearly define their research aim before coding students' SRL behavior. When aiming for a general overview, it is essential to use relatively broad coding categories (i.e., current research; task orientation, planning, rereading), while specific SRL strategies should be carefully selected and coded fine-grained if a more detailed picture is intended. This may seem obvious, but as the Disco process mining programme permits to quickly lower or add the number of activities included in the analysis, it may be appealing to start with fine-grained coding categories and to simply reduce the number of activities until an interpretable process map is obtained. However, this will influence the final results as it might appear that few micro level processes are decisive in students' learning process, while the actual picture is way more complex.

Further research is also needed to guide researchers in deciding on the number of activities and paths to be included in the process maps. As no guidelines exist in this regard, we decided to retain 33.3% of all activities and paths after careful deliberation among the authors of this study, all strongly affiliated with the SRL literature. This resulted in a process map that was informative, still interpretable and made sense from a theoretical point of view. On the downside, choosing this 33.3% cut-off implied that, for example, cognitive strategies such as summarizing, and memorising were not included in the process maps. While these strategies occurred very frequently in the group of high achievers, they were nevertheless adopted by a rather small share of learners and were therefore excluded from the maps. Therefore, we believe it to be essential that researchers are aware of this limitation and continue to combine descriptive results with process results in view of obtaining an accurate picture of students' SRL. Unfortunately, we believe that exact guidelines on the number of activities and paths to be included are not viable, as the ideal percentage strongly depends on the complexity of the process and the granularity of the data. Sharing good practices might, however, guide future researchers in making thoughtful choices.

Even though we consequently abstain from any guidelines in this regard, we believe it is advisable to mainly retain the balance between the percentage of included activities and paths. While it is technically possible, for example, to include 60% of the activities and 10% of the paths, we consider this less in line with the aims, the actual opportunities, and the added value of process mining. More particularly, when including more activities than paths, researchers might easily fall back into the current dominant trend of mainly reporting differences in the frequency of occurrence, rather than on focusing on the relation between SRL strategies in terms of sequences and patterns. When opting for the opposite (i.e., including more paths than activities), a very complex process map with seldom occurring patterns is obtained, while important strategies might still be missing.

At last, we believe that further research exploring different types of process mining is advisable (Bannert et al. 2014). While the present study used a discovery approach by building a process model on the basis of the event data (i.e., students' SRL activities and time stamps), process mining could also be used for conformance checking or, to a lesser extent, for enhancement (van der Aalst 2011; van der Aalst et al. 2011). Conformance checking implies that students' actual SRL process is compared to a pre-defined process model (van der Aalst 2011; van der Aalst et al. 2011). More specifically, students' actual text processing could, for example, be compared with the "ideal" process as defined by theoretical frameworks (e.g., Alexander 1998; Mayer 1996; Pressley et al. 1985; Weinstein et al. 2011). Doing so, students' degree of conformance or deviation from this model could be examined. Enhancement on the other hand could be used for enriching or refining the existing theoretical frameworks (van der Aalst 2011; van der Aalst et al. 2011) by comparing them, for example, with high achieving or experts' actual SRL process.

Limitations of the current study

While different limitations were already addressed in connection to the suggestions for future research, some additional limitations regarding both the measurement instrument and the analytical technique should be recognized. As to the first aspect, think-aloud protocols have, as all assessment methods, several advantages and disadvantages. On-line methods, such as think-aloud protocols, are very useful to map students' SRL activities during actual learning and to provide micro-level insight in the adopted strategies (Veenman 2011). On the contrary, they are usually applied in small samples as they are very time and labour intensive to collect and analyse. In the present study, a relatively large sample of students was included. However, this urged us, considering time and resource constraints, to strategically opt for not coding students' use of domain-specific SRL strategies in the assignments other than the study text (i.e., game, mathematics and French). While this was not the primary aim and scope of this study, we however believe that future research studying students' SRL processes in different domains, subjects, and tasks is certainly recommended (Greene et al. 2013; Schellings et al. 2013). A second, more general limitation of think-aloud protocols concerns the fact that they may suffer from incompleteness when learners do not manage to verbalize all ongoing thoughts or behaviours (Boekaerts and Corno 2005). Especially automated or unconscious behaviour might consequently not be mapped or not be mapped correctly. The current study, however, sought to limit this bias by both training students in thinking out loud and by coding verbal and non-verbal behaviour (Greene et al. 2011). In addition, it is possible that thinking out loud interferes with students' learning process and task performance. Prior research on this topic shows that different types of think-alouds interfere more versus less with students' cognitive process (Greene et al. 2011). More particularly, only verbalising conscious processes and behaviour *(type 1)* and verbalising cognitive processes that have no inherent verbal component (e.g., smell, emotions; *type 2)* appear not to interfere with students' learning process and performance. However, explaining the performed behaviour and thoughts *(type 3)* is known to influence students' learning (Greene et al. 2011). From this point of view, the current study only adopts type 1 and 2 verbalisations. This, however, has implications for the interpretation of activities and paths that occur in the process maps, as no information about students' underlying motives for their behaviour was obtained. Future research could prevent this by combining, for example, think-aloud protocols with retrospective stimulated interviews used for questioning students about the rationales behind the activities they conducted and the sequence in which they occurred. A final limitation of think-aloud protocols is the unsuitability for investigating students' motivation (Bannert et al. 2014; Vandevelde et al. 2015). In the current study, almost no utterance regarding students' motivation could be found in students' thinking aloud.

As to the limitations regarding the process mining techniques, it was already mentioned that to date, no standards exist on the amount of activities and paths that ideally should be included in the process maps (Fluxicon 2019). While the absence of these guidelines has advantages for studies with an exploratory scope, it has on the other hand consequences with regard to the comparability of study results as well. A second limitation concerns the absence of integrated, fine-grained theoretical SRL frameworks for interpreting the process maps. While there exist a variety of general theories on the SRL phases (e.g., Boekaerts 1999; Pintrich 2004; Zimmerman 2002), as well as more fine-grained theories on text-learning and information processing, (e.g., Alexander 1998; Mayer 1996; Pressley et al. 1985; Weinstein et al. 2011) to date, the connection between these frameworks is still lacking. Third, process models lend themselves perfectly for model and theory development, as has been shown in this study. However, a disadvantage of the applied technique is that the process mining models cannot be directly be related to statistical testing, such as significant testing (Bannert et al. 2014). Future research combining and integrating theoretical models and significance testing can enable researchers to better interpret and judge the appropriateness of students' SRL processes at a micro level. In this regard, a more widespread use of process mining could also contribute to the development of these frameworks and, as a result, to more thorough understanding of students' SRL strategy use.

Lastly, it should also be acknowledged that the findings and recommendations derived from this study are limited in scope. In this respect, SRL processes were studied in the specific context of task-specific study task within a classroom environment. Also, student grouping into low, average and high achievers was based on only one performance test. As already mentioned, future research is encouraged to corroborate our findings across different tasks (e.g., problem solving task), contexts (e.g., homework assignments etc.), ages (e.g., middle and high schools students), but also to triangulate a varied pallet of (SRL) assessment and performance measures to make accurate judgements on students (groups)' self-regulatory abilities (DiFrancesca et al. 2016).

Conclusion

In conclusion, the current study evidences that students generally adopt a cyclical SRL approach by going through a preparatory, performance, and appraisal phase during learning. Moreover, these phases are implemented in a rather flexible, adaptive manner as students often seem to repeat or return to prior SRL activities or phases. It should however be noted that clear differences in the quality of students' SRL process are present when considering differences between achievement groups. High achievers overall show a more strategic approach to learning than low or average achievers, as they more effectively orient on and plan different assignments (i.e., preparatory phase), more strongly and strategically combine cognitive strategies when actually processing information (i.e., performance phase), and more clearly adopt self-evaluation as a tool for monitoring and improving their learning.

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Compliance with ethical standrads

Conflict of interest The authors declare that they have no conflict of interest.

Appendix

See Tables 2, 3, 4 and 5.

Table 2 Coding scheme for analysing the use of metacognitive and motivational strategies during respectively all assignments (i.e., game, mathematics, French) and during the study text (based on Vandevelde et al. 2015)

Coding category	Phase	All tasks	Study text	Content	Examples—units of meaning
Task orientation	Prep	X	X	Exploring the task subject and constitution, detecting task demands, activating prior knowledge	E.g., Student screens the front and back of the document E.g., 'What do I need to do here?' E.g., 'It looks like a difficult text, it will not be easy'
Planning	Prep	X	X	Time management, strategic planning	E.g., 'I will start with the French words and then study the text" E.g., 'I will first read the text, then underline keywords and try to memorise the text'
Monitoring	Perf				
Strategic approach		X	X	Monitoring the strategic approach	E.g., 'I will have to reread this text once more later on'
Comprehension: confusion		X	X	Detecting lack of comprehension/mistakes	E.g., 'I don't know what this means; I don't know what I'm supposed to do.'
Comprehension: insight		X	X	Awareness of understanding	E.g., 'Ok, now I understand it'
Progress		X	X	Reflecting on the available time and the time schedule	e.g., 'I have already done 2 paragraphs, 3 to go; I will not make a summary as I don't have enough time left' E.g., 'Oh, it is already 4 o'clock'
Correctness		X	X	Interim checking of the correctness or completeness of task performance	E.g., During reciting, the student quickly looks at the text to check whether he remembers the information correctly E.g., 'I am checking whether I wrote everything in my summary; I think I made a mistake, I'm going to reread the paragraph'
Self-evaluation	App	X	X	Evaluating learning outcomes or learning process after task performance	E.g., 'Let's check whether I've completed all assignments.' E.g., 'I think I have studied the text thoroughly'
Motivational strategies	Perf	X	X	Positive self-talk, making tasks more interesting, increasing task value	E.g., 'I am pretending that I am teaching to my classmates, that is more fun' E.g., 'I will do my best, because I would like to get good marks'

Table 2 (continued)

Coding category	Phase	All tasks	Study text	Content	Examples—units of meaning
Affective reactions		X	X	Reflecting on self-efficacy, task difficulty, interest or value	E.g., 'I was good at completing these assignments E.g., 'It was harder than I thought' E.g., 'That was interesting'

In this column, the expected timing of the coded category in the SRL process is indicated (prep = preparatory phase; perf = performance phase; app = appraisal phase)

Table 3 Coding scheme for analysing the use of cognitive strategies during informative text studying (based on Vandevelde et al. 2015)

Coding category	Phase	All tasks	Study text	Content	Examples—units of meaning
Initial reading	Perf		X	Initial reading of the informative text on seahorses	E.g. Students reads a paragraph for the first time
Highlighting	Perf		X	Structuring text or structuring one's own notes	E.g., Highlighting key words during (re)reading of source text E.g., Student highlights the main branches of his Mind Map
Rereading	Perf		X	Rereading the source text	E.g., Student rereads the text out loud
Elaboration strategies	Perf		X	Paraphrasing text content, distinguishing main and secondary ideas, relating text content, providing personal remarks regarding the text content	E.g., Student repeats a couple of sentences in own words E.g., 'This is important, I need to remember this' E.g., Student looks at a picture and says: 'Here you see how a baby gets born' E.g., 'Uh, that is disgusting!'
Summarizing	Perf				
Non structured			X	Noting single key words or freestanding sentences	E.g., Student writes down: 'Baby: father pregnant'
Structured			X	Making a (graphical) summary with a clear structure or hierarchy	E.g., Student makes a summary and writes down full sentences E.g., 'I am going to make a Mind Map'
Memorising	Perf				
Knowledge telling			X	Memorising by rereading, copying or reciting the source text	E.g., 'Now I copy the text on my scratch paper' E.g., Student covers the source text with the scratch paper and tries to recite the text
Knowledge transforming			X	Memorising by rereading, reciting one's own summary or by answering self-prepared questions	E.g., I will now reread my summary E.g., Student turns to his scratch paper and tries to recite his notes

Table 4 Excerpt from a think-aloud protocol: transcript and coding

Example from transcript	Coding
[Reading the assignment] "Learn the text. Make sure you learn it well in order to be able to answer some questions about it."	Task orientation *Detecting task demands*
[Reading the titles] "The wonderful world of seahorses. General information"	Initial reading
[Reading the text] "Seahorses are mysterious, special creatures. Their head looks like a horse; therefore, they are called seahorses. This is also reflected in their scientific name 'Hippocampus'."	Initial reading
[Highlighting] "scientific name", "Hippocampus"	Highlighting
"That was important information"	*Elaboration strategies* Distinguishing main and secondary ideas
[Reading the text] "…as 'hippos' is the Greek word for horse"	Initial reading
[Highlighting] "Greek word", "horse"	Highlighting
[…]	
[Reading title] "Body structure"	Initial reading
[Scanning the image of the seahorse and indicating] "The spine is here. The head is here. The snout. The chest. The dorsal fin and the tail."	Elaboration strategies *Relating text content*
[Indicating on the image] "The spine. The head. The snout. The chest. The dorsal fin and the tail."	Memorising
[Reading the text] "As you can see on the image, the body of a seahorse consists of different parts.[…] If you look at the chest of the seahorse, you can see the difference between the two sexes: the male has a smooth chest."	Initial reading
[Looking at the image] "Ok, smooth so without spines…"	Elaboration strategies *Relating text contents*
[Reading the text] "and the female a serrated." […]	Initial reading

Table 5 Cued recall test questions and detailed answer key

Questions and scores	
1 Complete the following questions: *(2.25 p)* 'Hippos" is a Greek word. But do you remember its meaning? *(0.75 p) Correct answer: horse (0.75)* How do we know that seahorses are fish and not mammals? *(1.5 p) Correct answer: They breathe through gills (0.75) and have fins (0.75) or they breath just like fish (0.75)*	
2 How do seahorses get pregnant? *(4 p)* *Correct answer: the female deposits her eggs (1) and the male becomes pregnant (1)* Via a tube/ovipositor (1) (if the process is described 0.5 points, e.g.: 'ensures the eggs end up in the male' In the male's breeding pouch (1) (in case of incorrect key words or only 'belly': 0.5 points)	
3 Read the following statements and correct them when necessary. When there is no mistake in the statement, just write 'correct' underneath. *(2.5 p)* About hundred seahorses can be born at the same time *(1 p) Correct answer: wrong statement, about hundreds of seahorses can be born at the same time* Seahorses can suck up food from a distance up to 3 cm *(0.5 p) Correct answer: correct statement* Seahorses belong to the family of the zanders *(1 p) correct answer: wrong statement, seahorses belong to the family Syngnathidae*	
4 In the text there was a picture of a seahorse with indications of its body structure. Was the seahorse on this picture male or female? Explain why. *(2 p) Correct answer:* A female (1) because the belly was serrated (1)	
5 There may be no seahorses left in a few years. Why? Write down as many reasons as possible from the text. *(2.5 p) correct answer* (killed by people) to make beauty powder/cosmetics (0.5) (killed by people) to use as lucky pendants (0.5) To be sold as aquarium fish (0.5) They accidently end up in fishing nets (0.5) The place or sea wherein they live is polluted or destroyed (0.5)	
6 Read the text on crocodiles below. Write down all the differences you can find between the information regarding crocodiles and the text that you studied on seahorses. Pay attention: you can only use information from the text below and information from the text on seahorses! *(5.25 p)*	
Crocodile	Seahorse
Reptile	Fish (0.75)
15 species	35 species (0.75)
Wide forehead crocodile	Dwarf sea horse (0.75)
Especially lives in fresh water, sometimes in the sea	In seas and oceans (0.75)
Many teeth	No teeth (0.75)
Eat meat	Eat little animals (0.75)
Can hit hard with their tail	Tail moves fast but not hard (0.75)

Table 5 (continued)

Questions and scores
7 Translate the following words from French to Dutch: ‘un bruit’, ‘un exemple’, ‘assez difficile’. (*1.5 p*) Correct answers: Un bruit: a sound (0.5) Un exemple: an example (0.5) Assez difficile: quite difficult (0.5)

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