DIGITAL RESOURCE DESIGN AS A PROBLEM SOLVING ACTIVITY: THE KEY-ROLE OF MONITORING PROCESSES

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In this paper we analyse upper secondary school students' design of digital resources by interpreting digital resource design as a problem solving activity strongly influenced by the process of instrumental genesis. Our research questions concern the monitoring processes activated by students-designers. Through our analysis, we identified different levels of monitoring during digital resource design, highlighting how monitoring processes are influenced by the students' systems of conceptual and procedural knowledge and by the artifact's constraints.

INTRODUCTION AND BACKGROUND

The study presented in this paper sets in the mainstream of research focused on the role played by digital tools in the task-design process (Leung & Baccaglini-Frank, 2017). In different areas of disciplinary education, an increasing interest has emerged in investigating how the design process affects the designers' learning itself, focusing on the role that students could play as designers or co-designers of different kinds of digital resources (Kimber & Wyott-Smith, 2006; Tracy & Jordan, 2012). Few studies have focused on this aspect in the context of mathematics education (see, for instance, Diamantidis, Kynigos & Papadopoulos, 2019; Alessio et al., 2021). With the aim of contributing to this research issue, in this paper we analyse the process of digital resource design (in the following, DR-design) carried out by a group of secondary school students. In order to develop this analysis, we interpret the design process as a problem solving activity, as Shaffer (2007) does in his investigation of the nature of problem solving in architectural design, where design is conceived as a process aimed at resolving an open-ended problem through a series of intermediate solutions.

Most of the frameworks developed to investigate students' problem solving processes have identified specific phases that characterize them (see, for instance, Schoenfeld, 1985; Garofalo & Lester, 1985; Carlson & Bloom, 2005). Identifying these phases enables researchers to parse protocols of students' interactions focused on problem solving into episodes that can be classified according to specific categories (Schoenfeld, 1985). By investigating experts' problem solving processes, Carlson and Bloom (2005) characterise the problem solving process in terms of nested cycles of repeated actions. In particular, they noticed that experts move through four main phases when completing a problem: (a) *orienting*, when a mental image of the problem situation is constructed and the solver attempts to make sense of the question; (b) *planning*, when conjectures are initially devised and the playing-out of possible approaches is imagined; (c) *executing*, when the strategies devised during the planning

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phase are concretely carried out; (d) *checking*, when the focus is on assessing the correctness of the implemented approaches. When the first phase is completed, the planning-executing-checking cycle is repeated throughout the remainder of the solution process.

A key feature, within all the frameworks developed to explain the solvers' ways of dealing with problems, is represented by the importance of engaging in metacognitive behaviours to regulate own processes and make decisions. Schoenfeld (1985), in particular, focuses on *control*, defining it as a category of behaviour that deals with the ways in which individuals use the information at disposal and with the major decisions that they make when they are solving a problem.

Since good problem-solvers are not those that always make the right decisions, but those that can recover from erroneous decisions, Schoenfeld stresses that a major component of effective control consists of the periodic monitoring and assessment of solutions as they evolve. In tune with Schoenfeld's studies, Carlson and Bloom (2005) notice that experts monitor their thought processes and products regularly during all the problem solving phases, with the aim of both making decisions about their solution approaches and reflecting on the effectiveness of their decisions and actions. Here we refer to their definition of *monitoring* as "reflection on and regulation of one's thought processes and products at any point in the solution process" (pp. 54-55).

Carlson and Bloom (2005) highlight that, in the case of expert problem-solvers, the effectiveness of their monitoring is assured by their strong conceptual and procedural knowledge, since they could draw on this knowledge to verify the reasonableness of their results and the correctness of the actions they carry out. On the other hand, unstable systems of conceptual and procedural knowledge generate problems in activating monitoring processes (Schoenfeld, 1985). Lesh (1982) observes that, when the conceptual system is poorly coordinated, students risk to ignore salient features of a problem or to distort the interpretation of the problem situation. In case the procedural system is unstable, students' work is often characterized by rigidity in procedure execution and inability to anticipate the consequence of actions during the execution.

In the case in which the problem solving process under investigation is the design of digital resources for mathematics, both the identification of specific strategies to be implemented and the activation of effective monitoring processes are influenced not only by standard mathematical knowledge, but also by the knowledge about the digital artifact that is used and by the computational transposition of mathematical knowledge that the use of the artifact involves (Artigue, 2002). During the design process the digital artifact is gradually transformed into an instrument, by means of a process of instrumental genesis. This process works in two directions: on one side (instrumentalisation), the artifact is progressively loaded with potentialities and transformed for specific uses (Artigue, 2002); on the other side (instrumentation), constraints and potentialities of an artifact shape the subject's activity (Trouche, 2005), leading to the development of schemes of instrumented actions (Artigue, 2002).

Trouche (2005) distinguishes between three kinds of constraints: internal constraints (physical and electronic), command constraints (linked to the different commands and to the artifact's syntax), organization constraints (linked to the screen organization).

RESEARCH CONTEXT

The study presented in this paper involved 20 upper secondary school students (grades 12-13) who participated in a university STEM literacy program for students in secondary-tertiary transition (Alessio et al., 2021), which took place in the Polytechnic University of Marche in the period between October and December 2020. The part of the program devoted to Mathematics was aimed at giving students the opportunity to deepen their knowledge of specific mathematical topics through the use of GeoGebra as a tool for DR-design. It was articulated into 5 sessions (20 hours in total). During the first session, focused on the presentation of the GeoGebra software, the participants were involved in a guided design process in order to explore the features of the software and to gain confidence with its commands. The two following sessions were devoted to introducing a mathematical topic that participants had not faced at school: the theory of complex numbers. During the last two sessions, the participants worked in small groups (7 groups in total) and were asked to design two (or more) GeoGebra applets to support students' learning of complex numbers. Due to the pandemic emergency, most of the activities (including the working group activities) were developed at distance, by means of the Zoom platform. Three university tutors were always available to support the students during the DR-design process.

RESEARCH QUESTIONS AND RESEARCH METHODOLOGY

As mentioned above, the focus of the research documented in this paper is on students as designers of digital resources. The hypothesis on which our study is based is that, particularly in the case of students as designers, the problem solving process that characterizes DR-design is strongly influenced by the parallel process of instrumental genesis that characterizes students' construction of personal schemes in the use of a digital artifact and their appropriation of pre-existing schemes. The instrumentation process, in particular in its first phase, when several techniques and strategies appear to burst, could strongly affect the process of DR-design, due to the role played by the artifact's constraints in shaping the designer's activity.

Considering the key role played by metacognitive behaviours in regulating problem solving processes, in this paper we focus on the monitoring processes in DR-design and on the influence of the artifact's constraints and of students-designers' systems of procedural and conceptual knowledge on this monitoring. Specifically, we address the following research questions: *What kind of monitoring processes are implemented by beginner students-designers when they face the task of DR-design? How are these monitoring processes affected by the artifact's constraints and by the students-designers' systems of procedural and conceptual knowledge?*

In order to investigate these aspects, we video-recorded the working group activities with the aim of highlighting students' spontaneous in-the-moment discussions on their design process. The analysis of the collected video-recordings was performed according to the following steps: (1) transcription of the students' discussions and description of the actions performed by students on the shared screen during the DR-design process; (2) first qualitative analysis of the video-recordings' transcripts aimed at parsing the transcripts into episodes; (3) identification of the episodes during which students activate monitoring processes and analysis of these episodes to highlight their peculiarities and to investigate the effectiveness (or ineffectiveness) of these processes in supporting the DR-design.

During step 2, we classified the identified episodes according to Carlson and Bloom's (2005) four phases. To develop this classification, we interpreted these phases in relation to the DR-design process in the following way: (a) *orienting* corresponds to the initial phase in which the goals of the DR-design process are identified and the general structure to be given to the digital resource is agreed, by identifying its main components; (b) *planning* corresponds to the choice of the techniques to be implemented to create specific components of the digital resource; (c) *executing* corresponds to the implementation of a selected technique; (d) *verifying* corresponds to the activation of monitoring processes to highlight the effectiveness (or ineffectiveness) of the implemented technique in relation to the set goals. The planning-executing-verifying cycle is repeated each time the monitoring process highlights the ineffectiveness of an implemented technique.

DATA ANALYSIS

The results that we present refer to the analysis of the work carried out by the groups of students-designers in their first DR-design process, aimed at creating a GeoGebra applet to support students in the investigation of the different representations (algebraic, trigonometric, graphical) of complex numbers. Since all the students-designers were beginner designers, not having had previous experiences in DR-design, the DR-design process developed by the different groups was characterized by similar dynamics. Moreover, all of the participants had had few experiences in using the GeoGebra software. Due to space limitations, here we focus on the work carried out by one group of students-designers constituted by two girls (S, C) and one boy (V). The main protagonists of the design work are V, who shares his screen and works on the GeoGebra applet, and S, who poses herself as a guide for V. C rarely intervenes.

The *orienting* phase is almost missing in the work of the group. The students-designers immediately start to work on their GeoGebra file without previously discussing the general structure to be given to their applet. The result is that, from the very beginning, they proceed step by step: (a) setting single goals to pursue in the design process (constructing specific components of their applet); (b) identifying strategies to pursue these goals (techniques to adopt to construct each applet's component); (c) implementing these strategies; and (d) assessing their effectiveness. When students-designers think that they have reached each goal, they set a new goal and proceed through the same steps. In this way, the construction of the applet's components is developed without having clear the general structure of the applet and the relations between its different components.

In the following, we present our analysis of three short excerpts from the transcripts of the video-recording of the group's activity. These excerpts were selected with the aim of introducing paradigmatic examples of typical monitoring processes carried out by students-designers to assess the effectiveness of the techniques adopted to pursue specific goals. All the excerpts are focused on the first *goal* that students-designers set in their DR-design process, that is to introduce the algebraic definition of complex numbers and their representation on the Cartesian plane. Each excerpt corresponds to one micro-cycle of planning-executing-verifying and is presented by introducing the *techniques* adopted and implemented to pursue the goal and the *characteristics of the monitoring process* activated by students-designers.

Excerpt 1

The *first technique* that the group adopts to pursue the set goal is to create two sliders a and b and to write $z = a + ib$ in the input bar. GeoGebra recognizes $z = a + ib$ as a surface and the students-designers immediately realize that the representation that appears on the screen is not what they expected. The activation of an incorrect technique testifies students' weaknesses at the procedural level, in managing command constraints. The unexpected feedback from GeoGebra boosts a *monitoring process on the first technique* being implemented, leading students-designers to recognize the incorrectness of the chosen formula. This feedback is unexpected since it is not the result of an intentional process aimed at an aware activation of control strategies. The monitoring process is rapid and it simply consists in highlighting the need of adopting a different technique, without reflecting, at the conceptual level, on the reasons why writing $z = a + ib$ has produced an unexpected representation.

Excerpt 2

Although the monitoring process in excerpt 1 is not associated with deep reflections on the conceptual aspects related to the feedback received from the applet, it makes students-designers progress in their instrumentation process by exploring new formulas to be used. At the beginning of this exploration, V proposes to define a new point whose coordinates are a and b. S agrees and suggests to V to define this point by writing $A = (a; ib)$ in the input bar. This represents the *second technique* implemented by the group *to pursue their first goal*. When V writes $A = (a; ib)$ in the input bar, one tutor intervenes with a question for the group:

Tutor: Why did you write ib as a coordinate of the point?

S: Because… No! …It should be just b, since the *y*-axis is the imaginary axis.

The *monitoring process on the second technique*, activated by S, is boosted by the implicit feedback given by the tutor through his question. Therefore, also this monitoring process is not intentionally activated. Differently from what happens in excerpt 1, S not only proposes a correction of the second technique (to write b instead of ib), but she also explains the reasons behind the correction, showing awareness of the meanings associated with the ways in which the second technique is modified. In explaining these reasons, S effectively refers to her system of conceptual knowledge, recognizing the connections between the formula to be written in the input bar and the underlying mathematical knowledge.

Excerpt 3

Guided by S, V implements a *third technique*, which is simply the correction of the second technique adopted by the group and writes $A = (a; b)$ in the input bar. Then V starts moving the two sliders *a* and *b* and a silent verifying phase begins. Although, in students-designers' intentions, *a* and *b* should represent, respectively, the abscissa and the ordinate of the point, when V leaves the slider *a* fixed and varies the slider *b*, the point moves along a circumference centred in the origin, instead of moving on a line parallel to the y-axis. This problem is due to the fact that, since the coordinates of the point are separated by a semicolon instead of a comma, GeoGebra recognizes a and b as polar coordinates of the point A (not as cartesian coordinates, as students expected). The *monitoring process on the correction of the second technique* is intentionally activated: students-designers do not limit themselves to interpret the feedback received by GeoGebra or by a tutor, but intentionally interact with their applet to verify the effectiveness of the implemented technique. However, this process is ineffective since the students-designers do not correctly interpret the feedback given by GeoGebra when they interact with their applet, without noticing the problem related to the formula that they write in the input bar. The ineffectiveness of the monitoring process is due to their weaknesses both at the procedural level (they are not able to manage the command constraints) and at the conceptual level (they are not able to correctly interpret, in mathematical terms, the variation of the point when *a* and *b* vary).

DISCUSSION

In this paper we presented the results of the analysis of data collected during a study focused on the role of students as designers of digital resources. We analysed the DR-design process as a particular problem solving activity, by identifying micro cycles of planning-executing-verifying during the whole process. In particular, we focused on the monitoring processes activated by students-designers. The data analysis enabled us to identify different levels of monitoring, according to two main interrelated elements: the intentionality of the monitoring process and the students-designers' awareness in reflecting on their design at both the procedural and conceptual levels.

In excerpt 1, the monitoring process is not intentionally activated: students limit themselves to react to the feedback provided by the GeoGebra applet, recognizing that the representation that appears on their screen is completely different from the expected one. The decision that is taken (identify a different formula to be written in the input bar) is not motivated by explicitly referring to the related systems of procedural (the syntax of GeoGebra's commands) and conceptual knowledge (the mathematical meaning of the representation that appears on the screen).

In excerpt 2, it is the tutor that gives implicit feedback to the students-designers, so, again, the monitoring process is not intentionally activated. However, differently from what happens in excerpt 1, one of the students-designers (S) effectively draws on her systems of conceptual and procedural knowledge to reflect on the reasons behind the ineffectiveness of the second technique that was implemented.

Differently from the previous excerpts, in excerpt 3 the monitoring process is intentionally activated. However, this intentional monitoring process is not associated with an effective interpretation of what the students-designers observe on their screen. Their weaknesses at both the procedural and conceptual level prevent them from being aware of the connections between the ways in which they move the sliders *a* and *b* and the variation of the constructed representation.

The analysis of the three excerpts highlights the role played by the artifact's constraints (in particular command constraints) and by the students-designers' systems of procedural and conceptual knowledge in preventing them from activating effective monitoring processes. Since the command constraints are at the basis of the feedback provided by the applet, they could potentially boost students-designers' activation of monitoring processes that make them realize the need of adopting different techniques (like in excerpt 1). However, the students-designers' lack of awareness at both the procedural and conceptual level prevent them from activating intentional monitoring processes (like in excerpts 1 and 2) or from correctly interpreting the feedback provided by the applet in order to identify the reasons behind the ineffectiveness of an implemented technique (like in excerpt 3).

The fact that all the students involved in the study were beginner designers and had had a little experience in the use of the GeoGebra software clearly affected their DR-design. It implied, for example, that the orienting phase was almost missing in the DR-design of all the groups of students-designers, preventing them from having a clear overview of the structure to be given to their applet. Moreover, it prevented students-designers from carrying out effective monitoring processes by: (a) intentionally act on the digital resource, guided by anticipating thoughts about the expected effects of these actions; (b) correctly interpret the feedback provided by the digital resource to infer about the effectiveness of the implemented techniques; (c) reflecting in an aware way on the reasons underlying the effectiveness (or not) of the implemented techniques. Carrying out these kinds of processes requires a deep awareness of the mathematical knowledge related to the representations constructed through the applet and a stable system of procedural knowledge.

As a further step of our research, we plan to involve students-designers on a long-term program with the aim of investigating how the characteristics of their monitoring processes evolve when students progress in their experience of DR-design. Moreover, we plan to study what are the main factors that influence a positive evolution of students-designers' monitoring toward intentional and aware processes.

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