Embodied collaboration to foster instrumental genesis in mathematics

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Abstract: As cognitive science reports joint action requiring tight intercorporeal coordination between two partners, we aim to evaluate the role of this coordination in computer-supported instrumental genesis for mathematics. In our dual eye-tracking design study we developed an embodied activity that potentially contributes to technologically extended problem solving in trigonometry. We tested three versions of the design: (a) individual sensorimotor enactment only, (b) individual and then collaborative enactments, and (c) individual enactment and then collaborative description followed by enactment. As our first case showed, the required sensorimotor coordination was developed but never used in the following problem solving when a student worked alone. In contrast, in both collaborative cases the relevant sensorimotor coordination became a part of instrumented action scheme. Future research is needed to investigate if intercorporeal coordination with the other is crucial for the transfer of sensorimotor coordination from their original source to instrumental activity in mathematics.

Following an embodied turn in cognitive science, the design study presented here is a deliberate attempt to design a computer-supported environment for trigonometry so as to make explicit and observable the embodied and extended mechanisms of mathematical learning. There is a long tradition of research on learning mathematics with technology that extends student's thinking processes, including research on the teacher's role in its introduction (e.g., Drijvers, Doorman, Boon, Reed, & Gravemeijer, 2010); and growing body of literature on embodied mathematical learning. However, the interaction in CSCL has rarely been promoted and studied from an embodied and extended perspective, especially when it comes to more sophisticated mathematics such as trigonometry. In the tradition of an embodied interactive action-based design genre (Abrahamson, 2014), we designed tasks that invite students to establish new sensorimotor coordinations and later enact them within instrumented trigonometry problem solving. This *design study focuses on* the necessity and the preferred form of collaboration with a more knowledgeable other in the progress from pure motor activity to mathematics.

Theoretical framework

At the intersection of CSCL, E-approaches to cognition, and mathematics education, one can draw on multiple bodies of literature. Here we zoom in on embodied collaboration, computer-supported embodied design, and instrumental genesis as a prerequisite for technologically extended problem solving.

Embodied collaboration

In line with sociocultural traditions, we assume a student and a more knowledgeable other form a *functional system* when solving a problem task, with actions and cognition contingently distributed between the partners (Newman, Griffin, & Cole, 1989). Cognitive science has distinguished multiple embodied mechanisms that maintain the operation of this *intercorporeal distributed system*, such as fine adjustment to the trajectory of the other's action (Schmitz, Vesper, Sebanz, & Knoblich, 2017), or fine-grained predictions of the other's movements (Vaziri-Pashkam, Cormiea, & Nakayama, 2017). In mathematics education we can find traces of *embodied coupling* as tutors monitor a student's actions: the tutor's eye-movements reveal tight coordination with the student's movements (Shvarts, & Abrahamson, under review). Alternatively, the role of more knowledgeable other in embodied collaboration might be seen in a reciprocal *multimodal revoicing* of a student that provokes gradual transformation from personal embodied experience to socially established mathematical objects (Flood, 2018). The versions of the computer-supported activity that were tested in this study were designed to distinguish the influence of embodied joint action from verbal description, thus stressing the role of intercorporeal functional system versus collaborative naming in the genesis of a mathematical instrument.

Mathematical instrument and embodied instrumental genesis

In instrumental approaches to mathematics education an *instrument* is introduced as constituted from two sub-systems: an *artifact* and *instrumented action schemes.* A scheme is understood as "dynamic functional entity" in the complexity of its components such as "the goals and the anticipations, the rules of action, gathering of information, control-taking and the operative invariants” (Trouche, 2004, p. 286). For example, if a child uses a spoon (the artifact) to make sound on drums or to hit a nail (instrumented action schemes), the observable *sensorimotor coordinations* are similar, but the schemes are different as the goals of actions differ. The process in which a learner appropriates an artifact for a specific type of tasks is called *instrumental genesis*. Clinical studies make obvious the emergence of new sensorimotor coordinations in instrumental genesis: manipulation with a stick immediately enlarges peripersonal space, a blind person literally senses through a white cane (see de Vignemont, 2018, for broader discussion). With an eye on embodied CSCL, we focus on involvement of previously elaborated sensorimotor coordinations into mathematical instrumented action schemes.

Action-based design genre

Informed by embodied cognitive science, Abrahamson (2014) suggested a new genre of educational design for learning mathematical concepts with interactive technology, where a student is required to keep the screen green while moving her hands, thus developing new *sensorimotor coordinations*, traced in repetitive eye-movements in goal-oriented embodied activity (Duijzer, Shayan, Bakker, Van der Schaaf & Abrahamson, 2017). While at the beginning new coordination emerges as the solution of a motor problem, later it is transformed to mathematical conceptualization through collaboration with a tutor (e.g. Flood, 2018; Shvarts, & Abrahamson, under review). In this paper we question the necessity and investigate the form of this collaboration, in so doing we address the following *research questions*: How does collaborative versus solo performance influence the involvement of emergent sensorimotor coordinations into the future instrumental activity? How do perception, multimodal utterances and actions in a technological tutorial differ between embodied joint actions versus collaborative description of a student’s embodied experiences?

Methodology and materials

For our design study we have chosen trigonometry as a mathematics topic that requires spatial articulation, thus providing us with an opportunity to investigate motor and sensory activity by videography and eye-tracking. Unit circle is an artifact that contributes to understanding the trigonometric functions as having the same value appearing twice in each period (e.g., $\sin\alpha \quad \sin(180^\circ \quad \alpha)$). The *instrumental genesis stage* consisted of a set of four sensorimotor problems with color feedback, belonging to an action-based design genre (Abrahamson, 2014). Each task led the students to an embodied discovery in establishing new sensorimotor coordination in accordance to task constrains. In the series the additional mathematical notations were progressively added. As can be seen from Figure 1, the promoted embodied discoveries were: (task 1) keeping the hands at the same level (*a* and *b*); (task 2) keeping the colored angles the same size (*c* and *d*); (task 3) keeping the measures of two angles to be 180° in sum (not depicted here), and (task 4) keeping projection on the y-axis at the same height (*e* and *f*). The *problem solving stage* consisted of four trigonometry problems (e.g., $\sin\alpha \quad \sin 3\alpha$). We hoped to see that the artifact used to solve the forth motor-problem (Figure 1*d*, *e*) would next extend the students’ thinking and come to serve as the instrument for solving trigonometry equations.

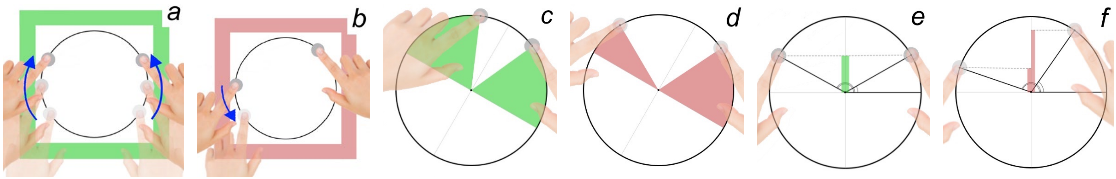

Figure 1. Figures *a*, *b* provide an idea of motor activity in task 1. Each pair of pictures represents two states: the target state with green feedback and incorrect state with red feedback.

This paper compares three versions of activity designs for undergraduate students learning. A graduate student in mathematics education program (Wes, all names are pseudonyms) took the role of more knowledgeable peer. Tim went through the motor problems of the instrumental genesis stage without any collaboration. For Rachel the individual sensorimotor practice was followed by a collaborative phase in which she performed the required embodied actions together with Wes (each one controlled one point and Rachel had to explain what to do). Diana, after her individual practice, had to answer the question about the rule that determines green feedback (the standard procedure for action-based design) and then also performed embodied joint action with Wes. Afterwards, all students went through the same problem solving stage. So, we trace three possible designs variations: *individual practice* (Tim), individual practice with the following *embodied joint action* (Rachel), individual practice with the following *collaborative description* of the rule and further joint action (Diana).

We used dual eye-tracking and videography to trace sensorimotor activity. In dual eye-tracking studies of CSCL often the interaction is limited to the speech channel and shared picture on the monitors, as remote eye-trackers are used (e.g., Sharma, Jermann, Nüssli, & Dillenbourg, 2013). In this research we used two head mounted Pupil-Labs eye-trackers that were calibrated on the surface of an interactive whiteboard. Later gaze paths were aggregated in one video. A micro-ethnographical analysis was conducted with the focus on the intercorporeal coupling between participants and on differences in instrumental activity between the cases.

Results and discussion

In accordance with previous findings (Duijzer et al., 2017), as students acquired fluent performance in each motor task, the iterative patterns of their eye-movements evidenced the emergence of new sensorimotor coordination. The eye-movements of the more knowledgeable peer as he was monitoring students' performance revealed tight coordination of his eye-movements with students' movements thus evidencing intercorporeal coupling between the tutor's perception and the student's action (cf. Shvarts & Abrahamson, under review).

Stage 1. Collaboration on instrumental genesis

Although both Rachel (*embodied joint action*) and Diana (*collaborative description*) needed to explicate their individual performance, their utterances were remarkably different.

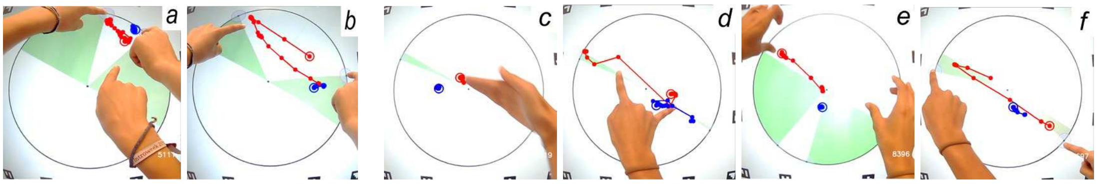

Figure 2. Rachel (a,b) and Diane (c,d,e,f) describe their embodied experience to Wes. The student's eye-movements are red, and those of the tutor are blue. On Figures *a*, *b* and *d* the right hand belongs to the tutor.

Rachel: Move that way (Figure 2a) … and and… I need to think how to explain it <...> Just keep going that way, slowly <…> A bit slower [than me]

Diana: We wanna keep the angle ... between this line (Figure 2c). The middle line ... and our point, this angle, <…> we want them both to be equal (Figure 2d). <…> we want this angle between the middle line and our points to be the same (Figure 2e).

Rachel repetitively uttered "that way" and "slowly" and pointed to the target direction. These rather vague references were sufficient though to sustain successful joint action. Apparently, their natural ability to predict (Vaziri-Pashkam et al., 2017) each other's movements and adjust (Schmitz et al., 2017) to them provided sufficient ground for joint task-efficient performance. Diana on the other hand used mathematically relevant descriptions of angles, supplemented by iconic gestures. So in her case, the description request led to an elaboration of culturally meaningful references (cf. Flood, 2018). Both students traced the joint performance by repetitive eye-movements (Figure 2*b*, *f*), thus contributing to intercorporeal coupling within distributed system.

Stage 2. Trigonometry problem solving

When they were asked to solve trigonometric equations, the usage of the digital artifact between the students trained in the individual (Tim) versus collaborative design versions (Diana and Rachel) was strikingly different.

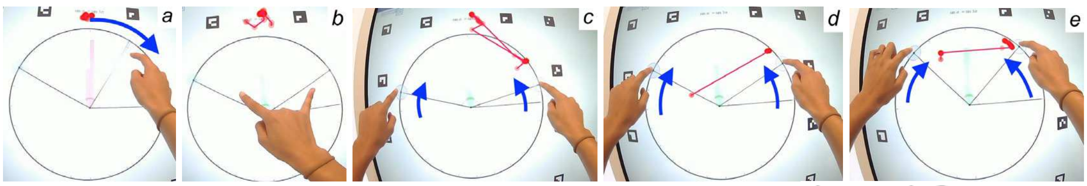

Figure 3. Diana enacts the target sensorimotor coordination as she solves $\sin\alpha$ $\sin 3\alpha$ equation. Eye-movements are in red. Blue arrows inserted to illustrate movements.

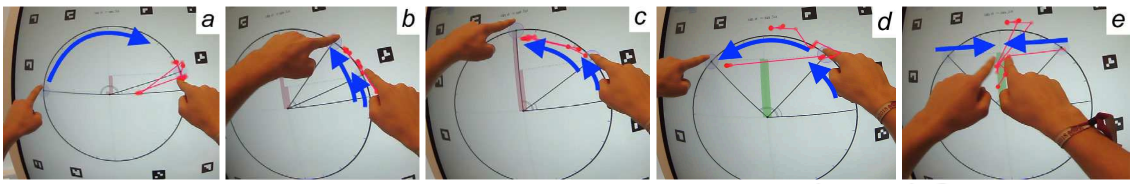

Figure 4. Tim invents a new instrumental action scheme as he solves $\sin\alpha$ $\sin 3\alpha$ equation.

Diana and Rachel immediately engaged in the sensorimotor coordination that was established in the four embodied tasks of the instrumental genesis stage: They positioned two points on the circle so that the sinus value of two angles became equal (Figures 3a, b) and then moved the points, keeping them at the same level (Figure 3c, d, e) until one angle became 3 times bigger than another one. Tim on the contrary did not use the artifact in the proposed way. After some unsuccessful attempts he invented his own instrumented action scheme: He moved the points to track two angles so that one would be three times larger than the other (Figures 4b, c, d) until the sinus value of the two angles became equal (Figures 4d, e).

Problem solving processes were very similar among all students who worked on collaborative versus individual versions of the design beyond the cases presented here. So the established sensorimotor coordination being relevant for problem solving became part of the *instrumental action scheme* for the technological artifact only when it had been enacted earlier or discussed in collaboration with the other.

Conclusions

In our design study we traced collaborative actions within an embodied computer-supported activity as well as dyads' multimodal utterances and eye-movements, and generated some novel hypotheses based on our results. We may expect individual *sensorimotor coordinations* as they emerge in a solution of interactive motor problems to be insufficient for instrumental genesis for mathematics. The comparison of the design versions suggested that a collaborative process is important for incorporation of the initial coordination into *instrumented action schemes* (Trouche, 2004): In both collaborative cases the students involved sensorimotor coordination, provoked by our embodied activities, in their technologically extended problem solving. In these cases, data revealed *coupling* between a student and a more knowledgeable other when the student and the other co-acted and when the other only observed the student's performance. The results contribute to understanding of embodied collaboration as forming an *intercorporeal distributed functional system*. Further research is needed to establish whether this intercorporeal coupling in joint action leads to the transfer of the initial embodied coordination to the mathematical domain, or whether a collaborative mathematical description of the student's experience is required. Unlike the explicit verbal description, the performance of embodied joint action did not require enculturated referencing and articulated iconic gestures. We propose that our design study contributes to understanding how embodied collaborative learning might lead to extended problem solving, and generates hypotheses that deserve investigation with a larger test group and the quantitative measures of gaze alignment.

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