Tracking Sensory Regulation During Embodied Learning with Electrodermal Activity: A Comparative Case Study

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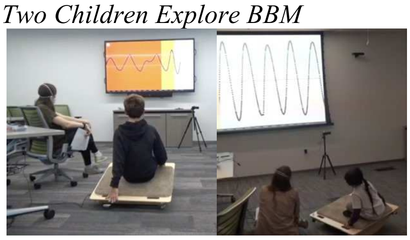
Abstract: Sensory stimulation from motor activity has been found to play a role in regulating learners' arousal levels. Although research on movement and learning is on the rise in the learning sciences, the impact of instructional designs' incorporation of movement on arousal regulation has not been examined. In this comparative case study, we explore whether and how sensory regulation of arousal unfolds in the context of a highly sensorimotor instruction. Within a larger design-based research project on balance-based math learning, we used electrodermal activity data to explore how the arousal levels of two participants with opposite sensory profiles varied in response to different types of sensory-stimulating movement, finding distinct arousal profiles for each child. Based on our findings, we outline hypotheses and possible next steps towards research integrating sensory regulation into conceptualizing embodied learning.

Introduction

Inspired by embodied cognition theory (i.e., Varela et al., 1991), a growing body of research in the learning sciences foregrounds the importance of children's bodily movement for their learning (Nathan, 2021). In parallel, occupational therapy research suggests that bodily movement stimulates the balance and body-in-space sensory systems, impacting children's arousal, a process called *sensory regulation* (Dahl Reeves, 2001; Lane et al., 2019). In this paper, we examine data from two contrasting participants in a design-based research project that integrates movement for learning and movement for arousal regulation: Balance Board Math (BBM). The BBM project focuses specifically on integrating rocking, which stimulates the sense of balance, into math conceptual exploration. As shown in Figure 1, students engage with mathematical concepts via movements on sensor-equipped balance boards. Students rock on balance boards while their movements generate real-time graphs on a digital display. They explore activities designed to foreground different mathematical concepts in functions and graphing. BBM constitutes an *embodied design:* a pedagogical design seeking to foster moving in new ways as the basis for thinking in new ways (Abrahamson, 2014). Findings to date in the BBM project have included observations of children engaging in rocking movements as both a means of thinking about mathematical concepts, and as a communicative tool to share and refine ideas (Tancredi et al., 2022). In the present paper, we focus on the sensory regulation aspect of BBM.

Figure 1
Two Children Explore BBM



One key BBM design conjecture is that of *sensory differentiation* of balance sensory input*:* learners can modulate the intensity of stimulation to their vestibular (balance) sensory system by choosing how quickly and how far to rock a wooden balance board. The sensitivity of an individual's neurology sets their optimal threshold for sensory stimulation– too little stimulation leads to under-arousal, and too much triggers overstimulation (Dunn, 2002). Those with high thresholds requiring high stimulation are *sensation-seeking*. In empirical studies with BBM (i.e., Tancredi et al., 2022), children's sensation-seeking profiles were associated with patterns in the intensity and frequency of their rocking. To further explore whether and how sensation-seeking might relate to children's movement and arousal patterns in an embodied learning context, in this paper, we contrast two children on opposite ends of the vestibular sensation-seeking spectrum. Given the lack of research in this area, we examine one comparative case study to generate specific hypotheses for future research that can inform sensory-inclusive pedagogical design.

In the present study, we operationalize learners' physiological arousal through the measurement of electrical changes in the skin: *electrodermal activity* (EDA). Increased conductance corresponds to increased physiological arousal, and EDA tends to increase over the course of a task (Dawson et al., 2016). EDA has been used to detect arousal in education research on stress, mental effort, and engagement (i.e., Di Lascio et al., 2018; Cain & Lee, 2016; Lee et al., 2019, Romine et al., 2022). This case study builds upon prior EDA work by exploring EDA variation in the context of an embodied learning activity featuring movement, investigating the relationship between a child's sensory profile and their electrodermal activity response to different sensorimotor tasks and activities. We pose the following exploratory questions:

1. How did standardized mean EDA levels and variability differ for two children with opposite vestibular sensory profiles?
2. Did EDA vary depending upon the type of rocking movement (elicited vs. non-instrumental) each child engaged in, controlling for time?

Methods

As part of a broader BBM study, 20 K-12 children completed semi-structured, task-based interviews exploring BBM. The latter 10 participants wore Empatica E4 EDA trackers on one or both wrists (two if alone, one if in a pair). We selected two children who participated individually, Tom and Jerry (pseudonyms), for this case study based on the completeness of their EDA data. We used a parent likert-style questionnaire, the Sensory Processing Measure 2 (SPM-2) (Parham et al., 2021), to measure each child's balance-motion percentile. Tom (a white male 8th-grader) was in the 24th percentile for balance/motion, the lower end of the typical range. Jerry (an Asian male Kindergartener) was in the 62nd percentile for balance/motion, the upper end of the typical range. Notably, his parent identified that he occasionally rocks, sways, or squirms when seated. We also computed the percentage of the interviews during which Tom and Jerry engaged in rocking: 14.5% for Tom, 47% for Jerry. Together with their SPM-2 results, we identified Tom as relatively low-vestibular-sensation-seeking and Jerry as high-vestibular-sensation-seeking.

Tom and Jerry completed a set of calibration activities: *EDA Calibration,* wherein to establish intraindividual arousal baseline, they watched a relaxing video. Next they completed *Board Calibration,* wherein they rocked on the balance board in a way comfortable to them, and then explored the basic mechanism of the graphing interface. Board settings were adapted to their rocking preferences, such as the speed of graphing and sensitivity of how board movements are translated to graphical output. After this, they participated in 3-5 randomly-ordered BBM discovery-based math activities. During each activity, they were given unlimited rounds to generate graphs. Participants were prompted to reflect on their strategies through semi-structured prompts by the interviewer, such as "Did that work how you expected?" and "What will you try next round?' We identified every instance of rocking in audio-video recordings of the interviews (Tom: 50.6 mins; Jerry: 39.8) using ELAN software. Informed by sensory regulation and embodied cognition theory, rocking was coded as Activity (all rocking to generate a graph on the screen), Non-Instrumental (background rocking, theorized to be sensory regulatory), or Conceptual (non-graphing rocking related to discussion and reflection of graphs, theorized to serve thinking and/or communication, i.e., rocking far to one side when describing a high peak on the graph). EDA data were averaged across both wrists for each second of the interview, and the z-score was transformed for each participant (range Tom: -1.766 to 1.719; Jerry: -3.481 to 1.087). To answer research question 1a, we used descriptive statistics and boxplots to compare the overall mean standardized EDA of Tom and Jerry and their mean standardized EDA when rocking vs. not rocking. We hypothesized that Jerry's EDA would be more impacted by rocking, meaning higher overall EDA and a greater increase when rocking. To answer research question 1b, we used multiple regression to predict EDA from (dummy-coded) movement type for each case study participant separately, controlling for time. The following statistical model was used for each:

$$y = \beta_0 + \beta_1\, Activity + \beta_2\ Conceptual + \beta_3\ Noninstrumental + \beta_4 * Time + \varepsilon$$

The regression coefficients $\beta 1$, β_2, and β_3 represent the mean EDA difference between each movement type and no movement, controlling for time. We controlled for time to ensure any cumulative impact of prolonged activity did not impact our analysis of movement type. Regression coefficients were tested against a significance level of 0.01. We used a Bonferroni correction to reduce the risk of type I error.

Results

EDA profiles

Tom's mean standardized EDA was 2.166 (SD: 1.321), whereas Jerry's was 10.713 (SD: 2.901). Tom's overall arousal level was lower than Jerry's, and as we predicted from their sensory profiles, his arousal level was less variable. Both Tom and Jerry's mean standardized EDA were higher when rocking (Tom: 0.07, Jerry: 0.392) than not rocking (Tom: -0.324, Jerry: -0.496), as was their median EDA. Jerry showed a greater difference between his mean rocking EDA and his non-rocking EDA, as hypothesized.

Regression model results

Tom's estimated mean standardized EDA during Conceptual and Activity movement was higher than when not moving: an estimated mean of 13.7% higher for Conceptual ($t_{2247} = 5.76, p < 0.001$), and 6.77% of standard deviation higher for Activity ($t_{2247} = 3.37, p < 0.001$), controlling for the effect of time. Thus, for Tom, the most alerting movement types were Conceptual and Activity, with no statistically significant difference found between these types ($t = -1.60, p = 1$). In contrast, Tom's EDA during Non-Instrumental movement was an estimated mean of 8.43% of a standard deviation lower than when he was not moving ($t_{2247} = -3.43, p = 0.001$). Non-Instrumental movement was also an estimated mean of 18.8% of a standard deviation less than Conceptual ($t = -6.58, p < 0.001$) and 14.86% of a standard deviation less than Activity movement ($t = -5.60, p < 0.001$). Thus, non-instrumental movement predicted relative calm compared to non-movement and to Activity and Conceptual movement. Overall, the regression model explained 86% of the variability in Tom's EDA data ($R^2 = 0.862$).

For Jerry, not moving predicted the lowest EDA. Compared to not moving, EDA during Non-Instrumental movement was an estimated mean of 43.4% of a standard deviation higher ($t_{1881} = 18.11, p < 0.001$), Activity movement was an estimated mean of 48.6% of a standard deviation higher ($t_{1881} = 15.89, p < 0.001$), and Conceptual movement was an estimated mean of 67.9% of a standard deviation higher ($t_{1881} = 22.63, p < 0.001$), controlling for the effect of time. EDA was highest during conceptual movement, followed by activity movement, as it was for Tom. Jerry's Conceptual movement EDA was more different from his Activity movement EDA than Tom's: Conceptual movement was an estimated mean of 19.31% of a standard deviation more than Activity movement ($t = 5.30, p < 0.001$). Unlike Tom, for Jerry, Non-Instrumental movement predicted a higher EDA than no movement; with no statistically significant difference from Activity movement ($t = -1.62, p = 1.00$). The estimated mean impact of Non-Instrumental movement was 24.54% of a standard deviation less than Conceptual ($t = -7.75,\ p < 0.001$). Overall, Jerry showed a greater impact of movement type on his EDA than Tom: the estimated mean impact of each movement type for Jerry was approximately five times greater than for Tom. This model explained 80% of the variability in Jerry's EDA data ($R^2 = 0.799$).

Discussion

We found differences in both baseline EDA and acute EDA changes that are consistent with sensory regulation theory hypotheses: overall, Tom, the less vestibular-sensation-seeking child, had a lower and less variable arousal level than Jerry. As predicted by the children's sensory profiles, non-instrumental background rocking had a larger impact on Jerry, the more vestibular-sensation-seeking child, than on Tom. Additionally, non-instrumental rocking had opposite effects on their arousal state. These findings are consistent with the hypothesis that children's sensory profile impacts their arousal variability, particularly with regard to the effect of sensory stimulation. Given that this is a case study, we can only hypothesize as to the reasons behind differences between Tom and Jerry's results. To test whether their sensory profiles indeed drive the differences between them, inter-individual research with a sufficiently large sample will be necessary, controlling for other factors that may impact sensory processing, such as children's ages.

The arousal levels of Tom, a relatively low-sensation-seeking child, and Jerry, a relatively high-sensation-seeking child, were each impacted by the context within which they rocked, be it as part of making a graph, reflection on and discussion graphs, or non-instrumental rocking (fidgeting). These findings are consistent with the design conjecture of BBM that sensorimotor stimulation inherent to embodied design activities may enable them to serve children's sensory regulation needs by modulating arousal. Consistent with prior EDA work showing higher arousal during greater cognitive load, we found that both Tom and Jerry's EDA increased when rocking as part of reflecting on graphs, as compared to generating them. Even though both generating graphs and thinking or talking about them entailed highly similar or identical physical rocking movements for the children, the eDA differences suggest a difference in cognitive activity. One promising direction for future work tracking

EDA in embodied design settings would be to use EDA as a possible predictor of breakthrough moments wherein children's mental effort and, consequently, EDA might decline.

We note several limitations to the present work. Firstly, a linear regression model may be too simplistic for the complex relationships present in physiological time-series data. We note high collinearity is an issue in our models, leading to a high conditioning number (Tom: 6.39×10^3; Jerry: 5.21×10^3); this is likely caused by a non-random distribution of movement types relative to time (for example a higher incidence of non-instrumental movement towards the end of the interview could lead to high collinearity with time). Other operationalizations of time such as using the different BBM activities in the interview may be a better fit to address this; Householder QR decomposition and/or a Principal Component Analysis could also help improve the robustness and accuracy of the regression analysis. A possible confound is that in this learning context, vestibular sensory stimulation and motor activity occur simultaneously. In future research, it will be important to distinguish the contributions of physical activity and sensory stimulation. The use of actuated boards could be a means for children to experience vestibular stimulation without a significant increase in physical activity. It could also control for differences in balance ability among children.

In conclusion, this comparative case study explores the sensory regulation aspect of embodied designs in complement to research on the conceptual benefits of such approaches. This pilot case study extends the common usage of EDA in more controlled settings, supporting its prospective utility in researching more naturalistic learning interactions. The patterns found here suggest, in keeping with research on sensory regulation, that sensory profile may indeed be useful in determining effective sensory differentiation to support children in maintaining optimal arousal levels that can support their learning. More broadly, it suggests the viability of research formalizing the relationship between sensory profile and sensory aspects of instructional design. Future work can test the hypothesis that sensory differentiated instruction regulates arousal, supporting learner engagement and consequently improving conceptual learning outcomes. Such research could inform how best to offer sensorially differentiated instruction for children across the sensory spectrum, towards more effective and inclusive instructional design.

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