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ARTICLE

Learning from errors in mathematics classrooms: Development over 2 years in dependence of perceived error climate

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Abstract

Background: Errors can provide informative feedback and exhibit a high potential for learning gains. Affective-motivational and action-related reactions to errors are two forms of error adaptivity that have been shown to enhance learning outcomes from errors. However, little is known regarding the development and contextual conditions of students' error reactions. A theoretically plausible facilitator to this end is the perceived error climate in the classroom.

Aim: We investigated how students' dealing with errors develops over time and which role the classroom context in general, and the perceived error climate in particular, has for this development.

Sample: A total of 1641 students participated in 69 mathematics classrooms in academic secondary schools.

Methods: Perceived error climate alongside students' self-reported individual reactions to errors were assessed in a 2-year longitudinal study with five measurement points over the fifth and sixth grade.

Results: Growth-curve modelling indicated an, on average, negative development of students' individual reactions to errors. This development varied substantially between classrooms and systematically depended on perceived error climate. A more positive error climate was associated with a less negative development of error adaptivity.

Conclusion: Taken together, our findings imply a strong need and considerable room for the teachers' support in developing and maintaining adaptive reactions to errors. They also allow for the conclusion that teachers can succeed here by means of realizing a positive error climate in class.

KEYWORDS

affective processes, cognitive processes, contexts of learning, error climate in the classroom, learning environments, learning from errors, metacognition, motivation, secondary/high schools

INTRODUCTION

Making errors is a pervasive element of learning processes in classroom and school settings and can provide opportunities for learning gains (Zhang & Fiorella, 2023). Errors have important functions in learning processes as they help to establish accurate mental models and, therefore, foster learning progress (Jones & Endsley, 2000). They are central in acquiring negative knowledge (knowledge about what does not work and what is not the case), which in turn has positive effects on performance (Gartmeier et al., 2008). Errors are defined as an unintentional deviation from a certain norm that prevents the realization of a specific goal and is judged to be incorrect (Zhao & Olivera, 2006). Examples include conceptual errors but also careless mistakes as a result of a lack of concentration. Despite being beneficial to learning processes, errors are often perceived as negative (Metcalfe, 2017). Consequently, students frequently show maladaptive reactions to errors, for example in the form of lessening learning activities (Oser & Spychiger, 2005; Zhang & Fiorella, 2023).

Research identified several personal determinants that predict different reactions to errors (for an overview, see Schunk et al., 2013). Research addressing specifically different types of reactions to errors additionally contributed to our understanding of the personal factors underlying more or less adaptive reactions to errors (e.g., Grassinger & Dresel, 2017; Tulis et al., 2018). While maladaptive reactions to errors are characterized by a decrease in learning motivation and an increase in dysfunctional affects such as hopelessness, adaptive reactions maintain a high learning motivation and functional affects such as joy, and lead to a responsive self-regulation of learning activities regarding the selection of learning tasks and the investment of effort and persistence—in other words, adaptive reactions to errors support the adaption of the learning process to the error at hand in a way that optimal learning progress results (Dresel et al., 2013; Steuer et al., 2013). However, relatively little is known regarding the development of adaptive reactions to errors over time as well as the contextual and/or instructional conditions thereof —although this would be of particular interest for educational practice. The concept of perceived error climate was suggested to describe contextual differences with regard to the handling of errors in the classroom context (Oser & Spychiger, 2005; Steuer et al., 2013; see also Van Dyck et al., 2005).

Against this background, we addressed how the students' self-reported dealing with errors develops over time and which role the classroom context in general and the perceived error climate in the classroom in particular play for this development. Reported are results of a 2-year longitudinal study in the subject of mathematics over the fifth and the sixth grade in academic secondary schools.

Individual reactions to errors

In the literature on learning from errors, at least two clusters of reactions are described, which can be more or less adaptive (Dresel et al., 2013; Grassinger & Dresel, 2017; Kreutzmann et al., 2014), and are distinguished in a similar vein also for learning from errors in organizational contexts (e.g., Keith & Frese, 2005; Rybowiak et al., 1999; Zhao, 2011) and other areas of self-regulation such as coping (e.g., Baker & Berenbaum, 2007; Folkman & Moskowitz, 2004). First, adaptive *affective-motivational reactions to errors* comprise the maintenance of learning motivation and functional emotions such as joy (or the effective regulation of dysfunctional emotions such as hopelessness, shame or self-threat). These reactions are strongly related to the self and have been extensively studied in recent decades as reaction patterns after failure under different theoretical perspectives (e.g., learned helplessness, attributional theory, achievement goal theory; for an overview, see Elliot et al., 2017). Second, adaptive *action-related reactions to errors*, which are related to the learning actions following errors, comprise the initiation of cognitive processes and behaviors aimed to specifically overcome a possible misconception underlying the present error. This includes analyzing the error, evaluating own knowledge, self-reflecting on underlying misconceptions as well as planning and conducting specific learning actions to overcome the error and misconceptions. Theoretically, this cluster of reactions is closely related to ideal-typical self-regulated learning and is more task-oriented than self-oriented (e.g., Winne & Hadwin, 1998).

A series of personal determinants have been identified to predict reactions to errors (for an overview, see Schunk et al., 2013). Primarily, self-related motivational tendencies and beliefs proved to be relevant predictors of adaptive affective-motivational reactions to errors. In detail, a positive self-concept, weak performance approach, and performance-avoidance goals as well as an incremental theory of own abilities were associated with the maintenance of motivation and positive emotions after errors (Dresel et al., 2013; Grassinger & Dresel, 2017; Kreutzmann et al., 2014; Tulis et al., 2018). On the contrary, primarily task-related motivational tendencies, specifically task value and mastery goals, were positively associated with adaptive action-related reactions to errors in these studies.

Regarding the interplay of affective-motivational and action-related reactions to errors, prior studies indicated that these types of reactions are clearly distinguishable from each other, so far demonstrated for the domains of mathematics, English, and German, and only correlate to a small to moderate degree (Tulis et al., 2018). Results from latent profile analyses underpin the assumption that adaptive affective-motivational reactions to errors are necessary but not sufficient for adaptive action-related reactions to errors, which are, in the narrower sense, responsible for the actual learning from errors (Grassinger & Dresel, 2017).

Concerning the effects reactions to errors have on subsequent learning and achievement, prior studies indicated that primarily action-related reactions are associated with learning effort, persistence, and achievement, whereas affective-motivational reactions only exhibit indirect effects on learning outcomes (e.g., Dresel et al., 2013; Grassinger & Dresel, 2017; Kreutzmann et al., 2014). These results are complemented by a set of studies and reviews highlighting the direct influence of self-regulated learning on learning outcomes (De Bruijn-Smolders et al., 2016; Jansen et al., 2019; Wang & Sperling, 2020) and a path model presented by Grassinger et al. (2018) indicating that affective-motivational reactions to errors encourage action-related adaptive reactions to errors which, in turn, foster academic achievement.

Development of individual reactions to errors

Regarding the developmental changes in the two types of reactions, relatively little is known, especially concerning primary and secondary education. To the best of our knowledge, the only existing study is from Grassinger et al. (2015), who analyzed linear changes in affective-motivational and action-related reactions to errors of students in secondary schools (grades 5–8) and found an average decrease in the adaptivity of error reactions. Notably, this decline was more pronounced when individual and contextual antecedents (mastery goals, self-concept, classroom goal structure) also developed negatively.

Several mechanisms are theoretically justifiable that may underlie the individual development of reactions to errors. First, the development of students' error adaptivity can be assumed to be dependent on the individual development of achievement motivation and emotions in general while still being clearly distinguishable from one another, as already indicated by the results of Grassinger et al. (2015) for slightly older children. If they develop in a positive manner, the psychological prerequisites of adaptive reactions to errors are given—if not, the risk rises for maladaptive reactions to errors. While motivational variables become more important for learning behavior and achievement over primary and secondary school, prior research indicates a tendential negative development thereof (Fischer & Rustemeyer, 2007;

Frenzel et al., 2010; Spinath & Spinath, 2005a, 2005b; Spinath & Steinmayr, 2008). Therefore, on average, a negative development of error reactions could be predicted. Second, as adaptive reactions can also be seen as specific types of processes of self-regulated learning, they may develop in an analogous way as competences for successful self-regulated learning (Wirth & Leutner, 2008). Metacognitive knowledge typically improves in secondary school (e.g., Artelt et al., 2012; Lockl & Schneider, 2002, 2003) just as cognitive competences and prior knowledge (Büttner, 2019), which in turn also fosters cognitive and metacognitive learning behaviors (Schneider & Bjorklund, 1992; Sontag et al., 2012). This could result in an increase in adaptive reactions to errors. Therefore, primary and secondary education is characterized by two developmental trends which are assumed to evolve concurrently: a negative motivational and emotional development and a positive development of cognitive factors, both with opposite influences on adaptive reactions to errors. Third, and most important, in the context of the present work, it is arguable to assume that the development of students' individual reactions considerably depends not only on personal conditions but also on contextual conditions, especially contextual conditions in the classroom. As contextual conditions vary substantially between classrooms (e.g., Meece et al., 2006; Steuer et al., 2013; Urdan & Schoenfelder, 2006), differential developments of the individual reactions to errors of students in different classrooms can also be expected. Accordingly, in the present work, we focus on the error climate in the classroom as a plausible contextual developmental condition for students' individual error reactions.

Error climate in the classroom as contextual antecedent

Based on Oser and Spychiger (2005), Spychiger et al. (1997) as well as van Dyck et al. (2005), a favourable error climate can be defined as the perception, evaluation, and utilization of errors as integral elements of the learning process within the social context of the classroom (Steuer et al., 2013). The error climate is primarily determined by the behavior of the teacher (in particular, teacher support after errors) but is also influenced by the behavior of classmates in error situations. On the whole, error climate comprises the quality and quantity of verbal and non-verbal interactions in the classroom context (Spychiger et al., 1997). Accordingly, the error climate can be understood as a classroom-specific characteristic that is assumed to vary between classrooms.

Steuer et al. (2013) proposed eight error climate subdimensions. The first aspect, (1) *error tolerance by the teacher*, comprises an error prevention or error avoidance attitude on the part of the teacher towards mistakes by students (e.g., only addressing questions to students from whom the teacher expects a correct answer). The subdimension (2) *irrelevance of errors for assessment* describes the extent to which student mistakes result in negative evaluations of student performance (i.e., grades). (3) *Teacher support following errors* refers to the measure of help (e.g., further explanations) offered by the teacher following student mistakes. The (4) *absence of negative teacher reactions* refers to the degree of disapproval in verbal and non-verbal reactions by teachers to student errors (e.g., demonstrations of anger and annoyance). The next two subdimensions deal with classmate reactions to errors. First, (5) *absence of negative classmate reactions* includes negative reactions by classmates, for instance, laughing or taunting. Second, (6) *taking the error risk* describes whether students are confident enough to say something during class without being completely sure if it is correct. The remaining two subdimensions refer to the social processes of learning from errors in a narrower sense. More specifically, (7) *analysis of errors* describes the magnitude of both analyses of errors and communication about errors, while (8) *functionality of errors for learning* describes whether errors are used to initiate learning processes in the classroom.

Prior work provided ample evidence from hierarchical confirmatory factor analyses with different samples of students that these eight error climate subdimensions contribute together to a uniform second-order error climate factor that was denoted as superordinated factor of the error climate in the classroom in the literature (Steuer et al., 2013, 2022; Steuer & Dresel, 2015). This superordinated factor provides a summarizing estimate of the several aspects of the perception, evaluation, and utilization of errors within the social context of the classroom.

Studies have also provided evidence that a positive error climate in the classroom is positively associated with adaptive individual reactions to errors (e.g., Grassinger et al., 2018). Specifically, results showed that perceived error climate in the classroom predicted the adaptivity of students' affective-motivational as well as action-related reactions to errors above and beyond perceived classroom goal structures (Meece et al., 2006) and personal achievement motivation (Steuer et al., 2013). Additionally, in the study by Steuer et al. (2013), perceived error climate was related to—partially mediated through students' individual reactions to errors—the quantity and self-regulation of students' effort. A constructive error climate has further been positively associated with motivational variables such as mastery goal orientation (and negatively with performance goal orientation), self-efficacy, and the willingness to put effort into learning as well as positive emotions such as joy (Kreutzmann et al., 2014) which, in turn, have been shown to positively influence adaptive reactions to errors (Dresel et al., 2013; Grassinger et al., 2015). Furthermore, studies provided evidence for interrelations between error climate and achievement in mathematics, English, and German (Käfer et al., 2018; Kreutzmann et al., 2014; Steuer & Dresel, 2015).

However, until now, only cross-sectional evidence exists in this field and to the best of our knowledge, no studies have yet examined the relevance of the classroom-specific error climate for the development of students' reactions to errors over time.

Research questions

Addressing the research deficits regarding longitudinal analyses of the development of students' individual reactions to errors and the relevance of contextual conditions in the classroom for this development, the present work thus examines two main research questions:

1. How does the students' dealing with errors develop individually over time?
2. Which role does the classroom context in general and the perceived error climate in the classroom in particular play for this development?

For reasons of theoretical parsimony and following earlier research, we focus on linear trends. As the age range beginning in primary school up until secondary school is characterized by a negative development of motivational factors on the one hand and a positive development of cognitive factors on the other hand (e.g., Artelt et al., 2012; Spinath & Steinmayr, 2008), it cannot be predicted in which direction affective-motivational as well as action-related adaptive reactions to errors are expected to change over the course of the fifth and sixth grade.

> **Hypothesis 1.** Affective-motivational as well as action-related adaptive reactions to errors change throughout the fifth and sixth grade.

Contextual conditions have been found to differ between classrooms, while the error climate has been shown to successfully capture contextual conditions in classrooms and further has been linked to adaptive reactions to errors (e.g., Grassinger et al., 2018; Kreutzmann et al., 2014; Meece et al., 2006). Therefore, it is expected that the adaptive reactions to errors vary between classrooms and the perceived error climate can predict the individual development of dealing with errors.

> **Hypothesis 2.** Differences in the development of affective-motivational and action-related adaptive reactions to errors exist between classrooms.

> **Hypothesis 3.** Differences in the individual development of affective-motivational and action-related adaptive reactions to errors can be attributed to differences in the error climate between different classrooms (the more constructive the error climate, the more positive or the less negative the development of reactions to errors).

METHOD

Procedure and participants

We used data from a 2-year longitudinal study in the subject of mathematics with five measurement occasions over the fifth and the sixth grade in German academic secondary schools (see Dickhäuser et al., 2017).

Measurement occasions were scheduled rather narrowly at the beginning of the fifth grade to allow for precise modelling of the changes after students' transition from elementary to secondary schools (which in Germany takes place after the fourth grade) and were scheduled less narrowly afterwards (see Singer & Willett, 2003). Measurement point 1 was scheduled in the first month in the fifth grade level, Measurement point 2 in the fourth month in the fifth grade level, Measurement point 3 in the sixth month in the fifth grade level, Measurement point 4 in the second month in the sixth grade level, and Measurement point 5 in the tenth month in the sixth grade level. The timespan between the first and fifth measurement point was 21 months.

For the present analyses, we used the data of all classrooms that participated in all measurement occasions and had the same mathematics teachers in the fifth and the sixth grade. We included students in the sample who participated in at least one measurement occasion. This resulted in 1641 students from 69 classrooms from 26 schools. At the first assessment, students' average age was 10.5 years (SD = .43), 53% were female. The mathematics teachers of the 69 classrooms included in the analysis had a mean teaching experience of 13.2 years (SD = 12.7) and a mean age of 40.7 years (SD = 12.9); 52% of the teachers were female.

Measurements

Students' self-reported reactions to errors were assessed at all five measurement points, and their perceptions of the error climate in the classroom were assessed at Measurement point 4. The time between measurement points was used as a time variable in the analyses.

Students' individual reactions to errors

Students' affective-motivational as well as action-related reactions to errors were assessed at all five measurement occasions using well-established self-report scales from Tulis et al. (2018). Prior studies have proven that the two qualitatively different reactions to errors can be measured validly and as distinguishable variables with this instrument (e.g., conducting confirmatory factor analyses)—this also includes studies with samples of students in a similar age range as in the present study (e.g., Dresel et al., 2013; Tulis et al., 2018). A sample item of the total of six items measuring students' adaptive affective-motivational error reactions reads: 'When I make an error in mathematics, then I will have less fun in math class later on' (reversed item).[1] Students' adaptive action-related error reactions were measured with seven items (sample item: 'When I do something wrong in mathematics, then I specifically try to work it out'). All items were presented with a six-point Likert-type scale ranging from 1 (*strongly disagree*) to 6 (*strongly agree*). Internal consistencies for the two scales were good to high at the five measurement occasions (Table 1).

Error climate in the classroom

Error climate in mathematics classrooms was assessed at Measurement point 4 via student perceptions of the eight error climate subdimensions, according to Steuer et al. (2013). In line with other contemporary approaches to assessing behavior in the classroom context (e.g., Lüdtke et al., 2005), it was assumed that students

[1]The complete list of items for all measurements can be found in an electronic supplement.

TABLE 1 Means, standard deviations, internal consistencies, and proportions of between classroom variance (ICC1) for all variables in the main analyses.

	M (*SD*)	Cronbach's α	ICC1
Adaptive affective-motivational error reactions			
Measurement point 1	4.70 (.87)	.83	.01
Measurement point 2	4.74 (.95)	.85	.04
Measurement point 3	4.66 (1.06)	.87	.06
Measurement point 4	4.42 (.98)	.83	.07
Measurement point 5	4.08 (.94)	.77	.12
Adaptive action-related error reactions			
Measurement point 1	4.86 (.73)	.84	.00
Measurement point 2	4.87 (.84)	.90	.00
Measurement point 3	4.81 (.94)	.90	.02
Measurement point 4	4.55 (.94)	.90	.07
Measurement point 5	4.18 (1.02)	.90	.06
Error climate (superordinated factor)	4.49 (.75)	.83[a]	.25

Note: $N=1641$ students in 69 mathematics classrooms. Error climate was assessed at Measuring point 4.

[a]Calculated with the eight subscales of the error climate instrument.

are able to observe the manifest behavior of their teachers and classmates associated with the perception, evaluation, and utilization of errors within the social context of the classroom in a differentiated way. A series of studies with students of different age groups (ranging from fifth to ninth-grade students) provided sound evidence from confirmatory factor analyses consistently showing that students' perceptions of the eight error climate dimensions form positively interrelated but clearly distinguishable dimensions (Steuer et al., 2013, 2022; Steuer & Dresel, 2015). It was also evident that students differentiate between judgements of the error climate and other instructional characteristics (e.g., classroom goals) and that students' perceptions of the classroom context are distinguishable from their self-reported individual reactions to errors (Steuer et al., 2013). Further evidence for the validity of this measure is provided by a quasi-experimental study with fifth grade students in which the error climate instrument was able to uncover differences between regular and error-friendly instruction (Soncini et al., 2021). A rather late assessment of students' error climate perceptions was realized as it can be assumed that students need considerable experience with a certain teacher and classmates to judge their behaviors adequately (see Kunter & Baumert, 2006). We used the instrument by Steuer et al. (2013) with 31 items in total to measure each of the eight subdimensions with three to four items (see Table 2 for sample items). Six-point Likert-type scales, which ranged from 1 (*strongly disagree*) to 6 (*strongly agree*), were used to assess the ratings. As listed in Table 2, the internal consistencies for the eight subscales were acceptable to high.

In line with prior work on the perceived error climate in the classroom (Steuer et al., 2013, 2022; Steuer & Dresel, 2015), we calculated a superordinate factor of the error climate as the mean of the eight subscales and used this score in our analyses. The internal consistency of the superordinate error climate factor was quite good also in the present sample (see Table 1). Moreover, intraclass correlation ICC2 as a measure of the homogeneity of student perceptions in the classroom was good for this measure (ICC2 = .87; see Lüdtke et al., 2009).

Missing values and data analyses

The rate of missing participants ranged between 6.7% and 14.3%. Item nonresponse occurred quite seldom (no more than 2.0% for all items). Overall, missing values occurred completely at random (Little's MCAR test: $p > .90$). They were imputed using the expectation–maximization algorithm (see Peugh & Enders, 2004).

TABLE 2 Sample items, means, standard deviations, internal consistencies and proportions of between classroom variance (ICC1) for the eight subscales of the error climate instrument by Steuer et al. (2013) assessing perceived error climate in the classroom.

Subdimension of the error climate	Number of items	Sample item	*M* (*SD*)	Cronbach's α	ICC1
Error tolerance by the teacher	4	In Math, our teacher doesn't like if something is done incorrectly.*	4.36 (1.08)	.78	.16
Irrelevance of errors for assessment	4	If someone in our Math class says something wrong, it has an immediate effect on their grade.*	5.03 (.93)	.87	.07
Teacher support following errors	4	If someone in our Math class can't solve an exercise correctly, the teacher will help them.	4.56 (1.13)	.86	.21
Absence of negative teacher reactions	4	If someone in our Math class does something incorrectly, they might be mocked by the teacher.*	5.02 (1.23)	.93	.21
Absence of negative classmate reactions	4	If someone in our Math class makes mistakes, their classmates will sometimes make fun of them.*	4.58 (1.18)	.91	.17
Taking the error risk	3	In our Math class, a lot of students don't dare to say anything because they are afraid it is wrong.*	3.52 (1.30)	.91	.11
Analysis of errors	4	In our Math class, we discuss it in detail when something is done incorrectly.	4.37 (1.07)	.88	.17
Functionality of errors for learning	4	In our Math class, wrong answers are often a good opportunity to really understand the material.	4.44 (1.01)	.86	.16

Note: $N=1641$ students in 69 mathematics classrooms. Negative sample items are indicated by an asterisk (generally, negative items were recoded before computing scale values).

We analyzed the data using growth-curve models with three levels: Level 1 represented measurement occasions, Level 2 the individual students and Level 3 the classrooms (Singer & Willett, 2003). General development in students' self-reported individual affective-motivational and action-related reactions to errors (Hypothesis 1) and existing classroom differences in these reactions (relevance of the classroom context in general, Hypothesis 2) were estimated by specifying unconditional growth models separately for both reactions to errors, which are defined by the following equations:

Level 1:	$\text{Error reaction} = \pi_0 + \pi_1 \cdot \text{Time} + e$
Level 2:	$\pi_0 = \beta_{00} + r_0$
	$\pi_1 = \beta_{10} + r_1$
Level 3:	$\beta_{00} = \gamma_{000} + u_{00}$
	$\beta_{10} = \gamma_{100} + u_{10}$

Here, students' reactions to errors are modelled as resulting from an interczept (π_0) and dependent on time (π_1). The intercept and the time effect were allowed to vary randomly between students and classrooms (random parameters r_0, r_1, u_{00}, u_{10}). To enhance the interpretability of the resulting coefficients, students' reactions to errors were standardized with respect to the first measurement occasion ($M_{T1}=0$, $SD_{T1}=1$). The time variable was coded in years—respectively, years in between Measurement point 1 (terminated at the beginning of the fifth school year) and the subsequent measurement points, resulting in the following time units for Measurement point 1–5: .00, .25, .42, 1.08, 1.75 years. By coding the time variable in years, regression coefficients of the time variable can be interpreted as change per year despite the varying time intervals between our measurement occasions (Singer & Willett, 2003). Due to the above-mentioned standardization, this change per year is quantified in Time 1 standard deviations of the outcome and, thus, can be interpreted as an effect size of standardized change per year (similar as Cohen's d).

The effects of the classroom error climate (indicated by students' perceptions of the error climate at Measurement point 4) for the development in students' individual reactions to their own errors (Hypothesis 3) were estimated with extended models, namely change as outcome models, again, separately for both reactions to errors, which are defined by the following equations:

Level 1:	$\text{Error reaction} = \pi_0 + \pi_1 \cdot \text{Time} + e$
Level 2:	$\pi_0 = \beta_{00} + r_0$
	$\pi_1 = \beta_{10} + \beta_{11} \cdot \text{Error Climate}_{\text{individual}} + r_1$
Level 3:	$\beta_{00} = \gamma_{000} + u_{00}$
	$\beta_{10} = \gamma_{100} + \gamma_{101} \cdot \textit{Error}\ \text{Climate}_{\text{shared}} + u_{10}$

In these models, the slope of the time variable (i.e., the strength of change over time) was predicted by student perceptions of the error climate in the classroom (superordinate factor). Therefore, the effects of the shared perceptions held by all students within a classroom (classroom aggregates, calculated as the arithmetic mean of the ratings of all students within a classroom), interpreted as an indicator for the actual error climate, are of primary importance (γ_{101}; grand-mean centred classroom means; see Marsh et al., 2012). Additionally, perceived error climate on the level of the individual student was included in the model (β_{11}; group-mean centred)—reflecting the importance of individual perceptions (e.g., Martin et al., 2011). Perceived error climate was z-standardized prior to analyses (shared perceptions were standardized on the classroom level, and individual perceptions were standardized on the student level).

RESULTS

Descriptive results

Descriptive statistics for all variables are presented in Table 1.[2] As visible in the ICC1, students' self-reported individual reactions to errors didn't differ systematically between classrooms at the beginning of the fifth grade. This may be due to the fact that classrooms are, in general, newly put together in this grade level in the German school system. However, classroom differences in students' individual reactions to errors increased over time for both forms of error reactions. This can be taken as a first indication of the (increasing) relevance of contextual factors. For perceived error climate, moderate to large differences between classrooms were found not only for the superordinate factor (ICC1 = .25; see Table 1) but also for all subfacets (ICC1 = .07–.21; see Table 2)—indicating that mathematics classrooms differ considerably with regard to all aspects of the error climate (for an interpretation of ICC1 see Lorah, 2018; Snijders & Bosker, 1999).

Average development of students' reactions to errors over fifth and sixth grade (Hypothesis 1)

Inspecting the sample means of students' adaptive reactions to errors revealed an, on average, negative development (Figure 1). While no mean changes worth mentioning occurred in the first half-year period of the fifth grade level, substantial decreases in the adaptivity of affective-motivational and action-related reactions were visible in the transition to and within the sixth grade level. The standardized differences between T1 and T5 (as measures of effect size) indicated medium to large-sized drops in the adaptivity of students' reactions to errors.

[2]Zero-order correlations between all variables can be found in an electronic supplement.

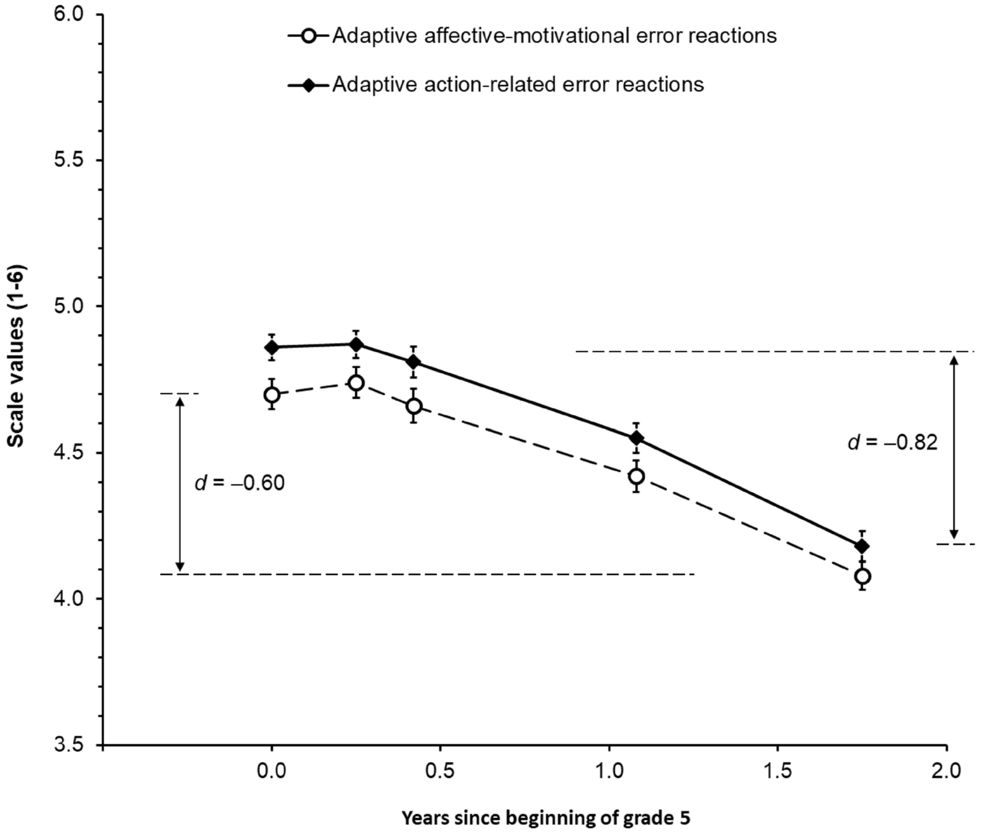

FIGURE 1 Development of students' adaptive reactions to errors throughout the fifth and sixth grade. Displayed are sample means with 95% confidence intervals. Effect sizes were calculated for the differences between Measuring point 1 and 5.

Results of the unconditional growth models (Table 3) confirmed this general negative development (with statistically significant negative fixed effects of the time variable). The pertaining coefficients γ_{100} indicate a negative development of both, adaptive affective-motivational and action-related error reactions of the students of about one-half of a standard deviation per year (H1).

Developmental differences between students and classrooms (Hypothesis 2)

Regarding the developmental change in the way students react to their errors, the slope variance of the time variable is of particular relevance. The unconditional growth models pointed to substantial differences in the development between individual students within classrooms (as indicated by significant random parameters r_1). These were descriptively larger for action-related than for affective-motivational error reactions. Moreover, it was obvious that the development in both, students' affective-motivational and action-related reactions varied significantly between mathematics classrooms—indicating that classroom factors exist that influence these developments (u_{10}).

Perceived error climate in the classroom and the development of students' individual reactions to errors (Hypothesis 3)

The change as outcome models (Table 3) estimated the effect of the perceived error climate in the classroom on the development of students' individual reactions to errors. As the statistically significant fixed effects

TABLE 3 Growth-curve modelling of students' adaptive reactions to errors.

	Unconditional growth model		Change as outcome model	
	Adaptive affective-motivational error reactions	**Adaptive action-related error reactions**	**Adaptive affective-motivational error reactions**	**Adaptive action-related error reactions**
Fixed effects				
Intercept γ_{000}	.10*	.10*	.10*	.10*
Time (years) γ_{100}	−.41*	−.53*	−.41*	−.53*
Error climate individual perception β_{11}			.31*	.26*
Error climate classroom mean γ_{101}			.15*	.15*
Random parameters				
Intercept variance				
Level 1: within students $Var(e)$	.54	.69	.54	.69
Level 2: within classrooms $Var(r_0)$	.69*	.71*	.69*	.71*
Level 3: between classrooms $Var(u_{00})$	.04*	.00	.04*	.00
Slope variance of time				
Level 2: within classrooms $Var(r_1)$	.18*	.31*	.16*	.28*
Level 3: between classrooms $Var(u_{10})$	.03*	.04*	.01*	.02*

*$p < .05$.

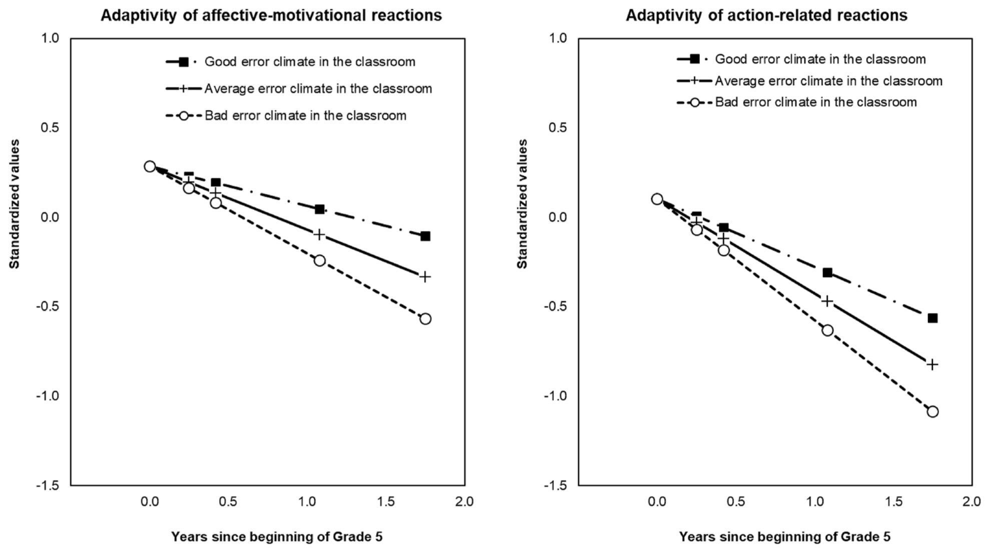

FIGURE 2 Predicted growth curves of students' adaptivity of reactions to errors for good (M + 1 SD) and bad (M − 1 SD) error climates in classrooms (classroom means of student perceptions).

indicate (γ_{101}), the development of adaptive reactions to errors systematically depended on the shared error climate perceptions in the classroom for affective-motivational as well as action-related reactions to errors. The more positive the error climate was perceived in the classroom, the less accelerated was the negative development of both forms of error adaptivity. A graphic representation of this development in dependence of more or less constructive error climates in the classroom can be found in Figure 2.

Above and beyond this effect of the average perceptions in the classroom, the development of adaptive reactions to errors also varied substantially within classrooms, systematically depending on the individual perceptions of the error climate (β_{11}). Again, the more positive the error climate was perceived on the individual level, the less accelerated was the negative individual development of affective-motivational as well as action-related reactions to errors.

The size of the effects of perceived error climate on the development of students' affective-motivational ($f^2 = .10$) and action-related ($f^2 = .16$) reactions to errors were small to moderate (see Lorah, 2018).

We additionally estimated the change as outcome model with each of the different subfacets of the perceived error climate in the classroom according to Steuer et al. (2013) in order to complement the results on the specific level. The pattern of results found for the superordinated factor was evident also for all subdimensions, that is, every single error climate subfacet was positively associated with a less negative development of students' affective-motivational and action-related reactions to errors, both on the level of shared perceptions and on the level of individual perceptions.[3]

DISCUSSION

The present work aimed at investigating how students' dealing with errors develops over time, which role the classroom context in general, and the perceived error climate as the theoretically most important factor in the classroom environment, in particular, has for this development. The study presented in this paper was the first longitudinal study to investigate the development of affective-motivational and action-related adaptive reactions to errors in dependence on the shared and individual perceptions of the error climate in the classroom (see Grassinger et al., 2015, for a preceding longitudinal analysis).

[3]Details can be found in an electronic supplement.

A broad sample of students and mathematics classrooms that was examined over the course of fifth and sixth grade levels with a larger number of measuring points allowed for precise estimations of the developments in students' reactions to errors (utilizing growth-curve modelling).

When examining the development of adaptive reactions to errors over the course of the fifth and sixth grade (Hypothesis 1), a decrease in self-reported affective-motivational as well as action-related adaptive reactions to errors was observable. These results align with prior findings of Grassinger et al. (2015), which demonstrated a similar negative development of both forms of adaptive reactions to errors. Based on our reflections on personal predictors, it was unclear a priori in which direction the adaptive reactions to errors would change due to the simultaneous negative motivational and positive cognitive development. It seems as if the negative motivational and emotional development that usually can be observed in the age range of the students in our study (e.g., Frenzel et al., 2010) outweighs the positive cognitive development in this age span (e.g., Artelt et al., 2012)—resulting in a development clearly in the direction from adaptive to maladaptive reactions to mathematical errors. Given the result of a negative development of error adaptivity, it seems likely that the positive cognitive development can't compensate for the negative motivational development and its effect on adaptive reactions to errors, at least in the domain of mathematics. In fact, some researchers assume a reinforcing effect of increasing cognitive and metacognitive development on the decline in motivation during adolescence (e.g., Eccles & Wigfield, 2020; Wigfield & Eccles, 2002). Accordingly, as cognitive development increases, children develop a heightened sense of self-consciousness as well as a better ability to see themselves and their performance in comparison to others. Paired with more evaluative feedback, especially after the transition to secondary schools, this cognitive development frequently has a negative effect on the (academic) self-concept and therewith, academic motivation.

In support of Hypothesis 2, the development of self-reported affective-motivational as well as action-related adaptive reactions to errors differed between classrooms. These results indicate the existence of classroom-specific factors that influence the development of adaptive reactions to errors individually in each classroom (Meece et al., 2006; Steuer et al., 2013; Urdan & Schoenfelder, 2006). Further, the development of error reactions substantially varied within classrooms as well. This can be interpreted as a reflection of the interaction of multiple determinants of the development of error adaptivity. Not only the classroom context a student experiences but also personal factors form one's error reactions and the development thereof. Consequently, the classroom context influences the development of error adaptivity but must be considered as one of multiple factors.

Finally, our results indicate that the perceived error climate—on the student as well as the classroom level—can successfully account for a substantial degree of the development of adaptive reactions to errors in mathematics classrooms (Hypothesis 3). Specifically, the results revealed a buffering effect of the error climate in the classroom: A more positive error climate obviously buffers the negative development of affective-motivational as well es action-related error reactions of students throughout the fifth and sixth grade. This pattern confirms and extends findings from prior cross-sectional research (e.g., Steuer et al., 2013, 2022). The unique contribution of the present findings is that they demonstrate a clear developmental influence of the perception, evaluation, and utilization of errors within the classroom context with their several sub-aspects as defined in the multidimensional concept of error climate (see Table 2). Further, the given results highlight the importance of both, the shared as well as individual perceptions of the error climate. Therefore, although the error climate is conceptually positioned at the classroom level and mainly determined by general teacher behaviors, individually varying perceptions that may result from perceptual expectancy effects on the side of the students or student-specific behaviors on the side of the teachers are similarly relevant and should be considered in theory and educational practice as well.

Limitations

When interpreting the results of this study, some limitations must be considered. First, the perceived error climate was assessed at Measurement point 4 which is rather late in the study. The rather late assessment was necessary to ensure that the students had enough time and experience to be able to judge the behavior of the teacher and classmates accurately (see Kunter & Baumert, 2006). This assumption is indirectly confirmed by the negligible classroom differences (ICC1) in students' error reactions at the beginning of the fifth grade when classrooms are newly composed and the only slow increase of such classroom differences over the course of the fifth and sixth grade. However, for causal statements, the error climate would be expected to be measured at the beginning of the study. In this context, it should also be mentioned that the perceived error climate was only surveyed once in the present study—based on the idea that the error climate is primarily influenced by the teacher (Oser & Spychiger, 2005) and that the teachers were the same across the 2 years observed. Nevertheless, possible changes in the error climate that may have influenced students' reactions to errors could have resulted from changing teacher behavior, for example. For future longitudinal studies, it seems advisable to conduct multiple error climate assessments in order to systematically analyze changes in the perceived error climate. Second, in the present study, we relied on students' self-reports of their own reactions to errors, which may be biased to a certain degree (e.g., social desirability, less consideration of situational characteristics). Although prior studies provided ample evidence for the validity of these measures (e.g., Dresel et al., 2013; Grassinger et al., 2015; Tulis et al., 2018), studies combining behavioral measures of students' reactions following errors (e.g., log data) with questionnaires would complement the present findings. Finally, as motivational variables tend to become more domain-specific in late childhood (e.g., Spinath & Steinmayr, 2008), these results should only be applied to mathematics and should no't yet be generalized to other domains. Including other domains in developmental approaches of adaptive reactions to errors should be the aim of further studies to be able to make statements about the generalisability of the found decline in adaptive reactions to errors.

Significance and conclusions

The present results highlight the importance of the individual and shared perception of the error climate for the development and maintenance of affective-motivational and action-related adaptive reactions to errors in an age span that is characterized by a general negative development of error adaptivity. In this, a strong need for the teachers' support is implied. They also allow for the optimistic conclusion that teachers can succeed here by means of realizing a positive error climate in class. Practical implications regarding specific instructional practices to achieve this refer to the various subfacets of the error climate concept (see also Oser & Spychiger, 2005). Considering teachers, this specifically includes tolerating errors as part of the learning process, not evaluating errors as negative, offering help following errors, and not showing any negative reactions to errors. Instructional approaches that utilize the potential of errors in a structured way (e.g., the productive failure approach; Kapur, 2010; Loibl & Leuders, 2019) offer additional opportunities to support students' learning from errors. The widespread positive effects of adaptive reactions to errors on academic achievement (e.g., Grassinger et al., 2018) emphasize the significance of the implementation of any means, including a positive error climate, that encourage error adaptivity in a scholastic context.

AUTHOR CONTRIBUTIONS

Markus Dresel: Conceptualization; funding acquisition; methodology; writing – original draft; writing – review and editing; formal analysis; investigation; supervision. **Martin Daumiller:** Writing – original draft; writing – review and editing; formal analysis. **Jana Spear:** Writing – original draft; writing – review and editing. **Stefan Janke:** Methodology; investigation; data curation; writing – review and editing. **Oliver Dickhäuser:** Funding acquisition; methodology; supervision; writing – review and editing. **Gabriele Steuer:** Methodology; investigation; conceptualization; data curation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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