An Interactive Web-Based Learning Platform for Arithmetic and Orthography

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Abstract: Numeracy and literacy are key competencies in modern knowledge societies with insufficient skills resulting in severe disadvantages on the individual and the societal level. Therefore, we are in urgent need for effective prevention and remediation programs corroborating numeracy and literacy. In the present article we describe the development and first evaluation of an interactive web-based learning platform for arithmetic and orthography, targeted at children after primary school. The web-platform hosts several training games for arithmetic and orthography for which general and specific training effects were found in a first evaluation. Additionally, we describe how intra- and inter-individual adaptivity may be implemented to the platform. In sum, results were promising for the use of web-based learning games to complement formal education.

Key-Words: Numeracy, arithmetic, literacy, orthography, game-based learning, adaptivity

1 Why do we need computer-supported interventions?

Numeracy (i.e., numerical and arithmetical abilities) and literacy (i.e., reading and writing capabilities) are not only important skills acquired during (school) education but are considered key competencies for everyday life at the beginning of the 21st century. Developmental disorders affecting these skills - also referred to as dyscalculia (numeracy) and dyslexia (literacy) - can occur either isolated or combined. Both are associated with severe disadvantages for the affected individuals but also our post-industrial knowledge society as a whole.

On the individual level insufficient numeracy (i.e., difficulties in handling numbers appropriately) has been shown to be detrimental for an individual's career and health prospects [1]. Additionally, untreated numerical learning difficulties lead to immense socio-economic costs. For instance, the annual costs of insufficient numeracy skills in the United Kingdom (UK) have been estimated at £2.4 billion [1]. These costs reflect the importance of mathematical education for economic success and future economic growth [2].

Similar problems are associated with developmental literacy disorders (i.e., reading and writing difficulties). They increase an individual's risk for school dropout, low educational achievement and unemployment but also cause behavioral and emotional problems [3]. On the societal level, the KPMG Foundation [4] estimated the annual costs for the UK arising from failure to master basic literacy skills to £2.05 billion.

To summarize, numerical and literacy education and in particular remediation of numerical and reading/spelling difficulties are specifically relevant to both the respective individuals but also to our societies [5]. However, there are currently hardly any intervention programs which have been demonstrated to allow for remediating such developmental disorders on a general level. As these disorders are largely resistant to conventional teaching methods we are in urgent need of new intervention approaches and techniques. Therefore, examining new possibilities to improve numeracy and literacy, such as the application of information technology and supportive counseling, is a strong endeavor for research and practice [6].

1.1 Computer-supported Interventions

While numeracy and literacy education have gained increasing research interest due to the PISA studies and their results, remediation research still lags behind. The majority of intervention programs still favor a classical paper-pencil based approach. However, as children are more and more used to latest computer and communication technologies (such as smartphones, tablets, etc.), these intervention programs may have problems motivating school children. Therefore, in the last 20 years, new technical approaches have been introduced and led to a number of evaluated computer-based programs which are argued to enhance intervention success (for arithmetic: e.g., scoyo, [7-9]; for orthography: e.g., Easy Training Program Version 3.0, EÖDL; Tintenklex Legasthenie Software Version 11, Dybuster, [10-12]). Although learning outcomes are partially promising, evidence is still too meager to allow overall conclusions.

1.2 Requirements and challenges

To mitigate spelling and arithmetic problems successfully, it seems necessary to identify the specific difficulties at a very fine-grained level and provide individually tailored programs supporting the specific learning needs. This calls for personalized learning programs that build upon an efficient and accurate assessment of individual deficits. Additionally, players in digital games seem to favor the opportunity to challenge and compete with one another [13]. Social interaction and competition, however, require a comparable skill level so that players apply more effort and play for longer periods of time [14]. Games with unmatched opponents only increase the enjoyment of players with a higher skill level. To address this issue, intra- as well as inter-individual adaptivity should be considered to ensure educational efficiency.

Additionally, information design (i.e., how to represent content and controls in visual interfaces, e.g., color coding [15-16]) and interaction design need to be specified [17-18]. For instance, the association of design principles and learning progress particularly applies to materials that induce high cognitive load and to learners who have little prior knowledge on the topic taught [19-20].

Using latest advancements in computer technology it is possible to create highly motivating and multimedia-enriched games with a combination of different media formats (e.g., text, audio, animation, etc. [21-22]) which may even allow for an adaptation to the learner's needs and skills.

Complying with these principles, the present project aimed at implementing and evaluating a web-based, socially interactive as well as intra-individually and inter-individually adaptive learning platform for arithmetic and spelling, which is based on latest theoretical and empirical evidence. To pursue this aim, the project was carried out in three steps. In the first step, we designed and implemented the platform and the respective arithmetic/spelling games. The second step involved a first roll out to the field, to evaluate children's performance changes in arithmetic and orthography through playing the games on the platform as well as to test its technical conditions and acceptance. In the third step, we started to realize intra-individual as well as inter-individual adaptivity.

2 Development of the Web-based Learning Platform

2.1 Design and Implementation of the Web-based Learning Platform

The web-based learning platform was developed in an inter-institutional cooperation between the University of Tuebingen and the Knowledge Media Research Center as an interdisciplinary collaboration of computer scientists, psychologists, and linguists (http://lernplattform.iwm-kmrc.de). Several learning games, targeted at children after primary school, were created as browser games which facilitate cross-platform playability, on personal computers, smartphones and tablets even outside the classrooms. The platform contains many components to make its use individually.

Fig. 1 Opening page of the Web-based Learning Platform

i) On a front page students can register and set up a profile in order to monitor learning progress and to enable social interactivity.

ii) Subsequent to profiling, an individual profile page is generated. Here, students have the opportunity to add personal information (e.g., age, gender, preferences for school subjects, etc.), but do not have to disclose personal data. These profiles are similar to widely known social networks accounts and might enhance communications among students.

iii) Third, the platform provides a chat forum to allow for communication between students (also while playing a game) and to contact psychologists and programmers if necessary. Figure 1 illustrates the provided opportunities for users.

A core feature of the learning platform is that it allows playing against other players (up to 5) and interacting with them in terms of a real-time chat component as well as playing against computer-controlled opponents. To provide this interactive gaming experience, client-server architecture was established. This architecture is based on the Google Web Toolkit (GWT). It includes a Java-to-Javascript compiler allowing for the development of rich internet applications in Java. Thus, the whole application can be written solely in Java. GWT contains implementations of commonly used classes of the Java standard library (i.e., most of the java.lang and java.util classes). It also provides a development mode. In this mode the application can be tested within a regular browser and it supports JUnit (a unit testing framework). In addition to the mentioned features, GWT also comprises a large library of widgets and panels. Finally, GWT provides several built in methods to communicate with a server. Remote procedure calls are among these methods and are used in the implementation of the web-based platform.

User data generated while playing the games are logged on a database server system running the object-relational database management system PostgreSQL for subsequent data analysis [23]. User actions logged are, for instance, textual input, touchpad/mouse movement and current game states (e.g., timestamps and counters) to capture the actual gameplay. In this manner students' developmental trajectory can be documented and analyzed. Archived over longer periods of time, these logs provide crucial input for an extensive analysis of gamer performance and development. Moreover, they are essential for realizing intra- and inter-individual game adaptation.

2.2 Design and Implementation of the Learning Games

As the quantitative basis for the learning games basic numerical and orthographic skills were assessed in more than n=400 5th and 6th graders. In this data set, students with numerical and/or spelling difficulties [24] as well as developmental trajectories for the respective competencies could be identified [25-26].

Altogether, four numerical and four spelling games were designed and implemented on the web platform. The numerical games, to begin with, have been designed considering latest results from our research on number processing [26-27]. The majority of these games are developed as choice-reaction tasks. In such tasks two or more possible solutions to a problem are presented:

i) ‘Multiplication’ is a game for training multiplication facts. Students have to indicate which one of a variety of multiplication problems corresponds to a given result (e.g., 72, with the solution 8 x 9).
ii) In the game ‘Partner number’, students have to indicate which number needs to be added to a given number to add up 10 (e.g., 6 needs to be combined with 4 to add up 10).
iii) The ‘Carry Game’ is an extension of the game ‘Partner number’. This game specifically trains the procedure of the carry-over operation in addition. At first, the students have to choose an addition problem (e.g., 7 + 5 = 12). Then they have to indicate which solution probe needs to be added to the first summand (e.g., 7) to add up to 10 (solution: 3). Next, they need to choose the number that adds up to the solution (i.e., 12) of the initially selected problem (solution: 2). Both games ‘Partner number’ and ‘Carry Game’ are used for training the place-value base-10 structure of the Arabic number system [28].
iv) The ‘Number Line Game’ aims at enhancing children's performance in number line estimation, and thus, their mapping between numbers and space [29]. In this task students have to mark the correct position of a number on a number line by clicking on the estimated position with the mouse curser. After a student has set her/his mark, slower opponents cannot place their marker at or around this already occupied location. Thereby, fast and accurate estimation is required whereas too slow but accurate strategies or too fast but inaccurate strategies are not successful.

As regards spelling, four games were designed to train different aspects of German spelling rules:

i) In German, double consonants usually follow a short vowel (with a few exceptions). The ‘Gemination Game’ trains phonological awareness of short and long vowels, because this skill seems to be an essential requirement for correctly producing consonant geminations [30-31]. To accomplish this, the game is divided into an identification (i.e., identification of the vowel’s length) and production (i.e., writing the target regarding the gemination rules) phase. During identification, the students have to decide whether an auditorily presented word contains a short or long vowel (e.g., ball). This phase is followed by a mini-game in which students have to collect coins showing the same double consonant as identified in the target word (e.g., ll). Subsequently, in the production phase students are required to spell the target word correctly by typing it in. Direct feedback is given in the identification and the production phase.
ii) The game “LeTris” is similar to the well-known computer game “Tetris” and trains the production of consonant geminations. First, students hear a word spelled with a gemination (e.g., bitter). Subsequently, letters start to come off the playing field one after another (e.g., e, t, b, etc.) and need to be arranged properly. When the word is spelled correctly the line including the composed word clears away (as in Tetris). In case they fail, the respective letters remain in the playing field. Thus, the more words are spelled incorrectly, the more remain in the field, finally leading to game over.
iii) Words refer to ‘Word Families” if they share the same root (e.g., to read, reading, readable, etc.) or morpheme (e.g., read-). Such relationships have been shown to facilitate literary performance [32]. In the game ‘Word Families’ ‘students have to memorize as many words as possible (e.g., familiarity, familiar, familiarize, etc.) that belong to the word family of an initially presented target word (e.g., family). Subsequently, they have to type-in and spell correctly all words they can remember.
iv) The game ‘Word Building Blocks’ is also based on the principle of word families. A selection of morphemes (e.g., heat, new, and know) and various other words containing one of these morphemes (heater, newly, unknown, etc.) is presented. Next, students have to indicate which word belongs to which word family. Both games ‘Word Building Blocks’ and ‘Word Families” train the awareness for morphological consistency, shown to support the development of correct spellings [31].

3 Evaluation of the Web-based Learning Platform

In a first evaluation of the platform, intervention effects of three of the arithmetic (‘Multiplication’, ‘Partner Number’, and ‘Carry Game’) and three of the spelling games (‘Gemination Game’, ’Word Families’, and ‘Word Building Blocks’) were evaluated in 5th and 6th graders.

3.1 Material and Methods

Two 5th and 6th grade classes (n = 31) of two public secondary schools (Hauptschule) in Baden-Wuerttemberg, Germany, participated in this pilot evaluation. Some children did not attend all assessment sessions. Therefore, data sets of only 24 children (10 female) and 23 children (9 female) were used for the evaluation of the arithmetic and the spelling training, respectively. All children and parents as well as schools gave their written consent to participate. The study was implemented as a cross-over design. One class (group 1) received three sessions of the spelling training first, followed by three sessions of the arithmetic training (both about 45 minutes each). This procedure was reversed for the other class (group 2).

Subsequently, game partners were selected by the respective class teachers as they were able to assess children's individual level of competency and match them according to their performance. This allowed for competitive playing within those pairs of children. Due to relatively low bandwidths, and thus restricted upload capacities (max. 128kB/s), and problems to resort to a locally installed server, the schools' computer facilities could not be used. Consequently, a so-called mobile class-room using laptops with several local servers was set up. These laptops were connected in pairs via local LAN cables (i.e., one laptop as server hosting the whole web-based learning platform, the other as client).

Both arithmetic and spelling performance was assessed at three time-points to track the learning progress (i.e., at the beginning, after three and after six training sessions). Arithmetic skills were assessed by a speeded paper-pencil test, realizing two difficulty levels for all four basic arithmetic operations: addition (easy: 18 no-carry problems; difficult: 18 problems of which 9 required a carry operation), subtraction (easy: 15 no-borrow problems; difficult: 15 problems of which 7 required a borrowing operation), multiplication (easy: 28 single-digit problems, difficult: 14 single- digit x two-digit problems), and division (easy: 28 problems with single digit divisor and result; difficult: 14 problems with single- and two-digit divisor or result). For easy problems the time limit was 30 seconds, for difficult problems 1 minute.

In the spelling assessment children had to perform a writing-to-dictation task and completed 28 gapped sentences by a respective target word (e.g., 'Der Wind _______ (weht) heftig.' - 'The wind ________ (blows) fiercely.'). Target words covered all central orthographic aspects of German written language such as capitalization of initial letters, gemination and lengthening signs.

Data analysis was performed separately for the arithmetic and spelling training, as differences in the assessment (i.e., speeded task vs. non-speeded task) did not allow for combined data analysis.

For evaluating the effects of the arithmetic training, linear mixed models (LMM) were used to contrast influences of type of training (arithmetic or orthography training) as well as problem type. The models included a random intercept for children.

For the analysis of orthographic skills, all variations of misspellings were collected and linked to the individual child. Data analysis was based on item response theory models (IRT). These models are able to separate the effects of the item (e.g., item difficulty) from effects of the person (e.g., person ability) in explaining the observed behavior. In particular, the Linear Logistic Test Model (LLTM, cf. [33]) was used to evaluate performance changes over time and training effects. In this vein, the same items presented at different tests points were considered as "structurally" different, as they are expected to change in difficulty over time. Moreover, the LLTM allows for decomposing item difficulty differences between several test points into an effect of training and a general temporal trend.

All analyses were run using the statistic software R (R Core Team, 2014). The packages lme4 [34] and lmerTest [35] were used to perform linear mixed effects analyses and to derive *p*-values for mixed models. The eRm package [36] provided conditional maximum-likelihood estimation of the parameters of the Linear Logistic Test Model. The criterion of statistical significance was set at α=.05.

3.2 Results

3.2.1 Arithmetic

Analyses indicated that the arithmetic learning games had a beneficial effect on children's arithmetic performance. A significant main effect of problem type was found (LMM: $F_{1,\ 367.9} = 6.51$, $p<.001$), whereas type of training was non-significant (LMM: $F_{1,\ 367.9} = 0.54$, $p=.461$). However, the interaction of both factors was also not reliable (LMM: $F_{1,\ 367.9} = 0.88$, $p=.524$) indicating no specific training effect of the arithmetic games. Training effects were observed only for easy tasks regardless of the operation; and non-trained operations such as subtraction did not yield any performance improvement after the training. The three arithmetic games ('Multiplication', 'Partner Number', and 'Carry Game') trained simple addition and multiplication skills, thus, significant effects on easy addition (Least square means (LSM) ± SE = .791 ± 0.31, Confidence Interval (CI) = .182-1.401, *p*= .011) and easy multiplication (LSM ± SE = 2.208 ± 0.31, CI =

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1.599-1.338, $p= .019$) as well as its inverse operation of division (LSM ± SE = 0.729 ± 0.31, CI = .120-2.817, $p< .$) were observed.

Apparently, children demonstrated an increase of performance independent from the preceding type of training. This indicates that general time-series effects cannot be neglected to explain improvements in arithmetic performance.

3.2.2 Orthography

For analyzing the change of orthographic skills during training, the LLTM was fit to the data. Accordingly, the design matrix of LLTM was constructed modelling test points (3 time points), group membership (2 groups) and response format (0: spelling incorrect, 1: spelling correct).

The estimated coefficient for the effect of intervention was significantly different from zero (Effect of intervention: Estimate ± SE = 0.651 ± 0.28, CI = 0.100-1.202; Temporal trend test time 1 to 2: Estimate ± SE = 0.302 ± 0.21, CI = -0.111-0.716; Temporal trend test time 2 to 3: Estimate ± SE = -0.133 ± 0.21, CI = -0.554-0.287). Hence, children's performance improved specifically due to the spelling training. However, for group 1 (arithmetic training from time 2 to time 3) there also was a decline in the ability parameter between test time 2 and 3. At the group level, the mean model predictions of expected correct responses estimated by the LLTM were very close to the observed mean number of correctly written words.

3.3 Discussion and implications

The purpose of this study was a first roll out to evaluate 5th and 6th grade children's performance changes in arithmetic and orthography trough game-based learning on a web-based learning environment as well as the technical conditions and the acceptance of the platform. In the following we will first discuss the observed learning effects before elaborating on technical issues and acceptance of the learning platform.

3.3.1 Learning Effects

The arithmetic learning games (Multiplication', 'Partner Number', and 'Carry Game') were effective in improving mathematic achievement scores, at least for the operations trained directly (i.e., addition, multiplication). Transfer effects from addition to subtraction were not observed. However, there were reliable improvements in simple division possibly mediated by multiplication training [37].

However, the learning effects due to the arithmetic games were not specific, since similar learning effects were also obtained after the orthographic games. A possible explanation for this result might be that arithmetic games successfully trained specific abilities (after all, we observed training effects), but some training effects of orthography improved arithmetic performance as well (i.e., sequential, symbolic and spatial processing). Moreover, it is conceivable that some children might have trained at a too easy or a too difficult level, thereby reducing possible specific improvements. Implementing built-in adaptivity of the web-platform may help to overcome this shortcoming (see below).

In contrast, the learning effects for orthography were very promising. A significant differential intervention effect was found for the spelling games 'Gemination Game', 'Word Families', and 'Word Building Blocks'. This effect indicates significant improvement in children`s overall spelling performance through the orthographic learning games. This is in line with previous findings showing that training of phonological awareness and morphological consistency corroborates the development of spelling skills [30-31]. Additionally, it further substantiates the applicability of online learning games for an (implicit) mediation of orthographic knowledge. We are aware that the number of children participating in the present study is rather small. Usually, larger samples are used for LLTM and Rasch models to obtain robust parameter estimates. Nevertheless, even though statistical power was rather small, the effects found in the present study were significant and promising with respect to the exploratory purpose of the first evaluation of our web-based learning platform.

3.3.2 General Implementation Issues

Implementations of such a web-based learning environment - in particular in schools - can be hampered by problems originating from technology. Thus, implementation designs should be highly flexible in order to compensate for infrastructural problems as well as for hard- and software issues [38]. As regards the present evaluation, computer rooms in the participating schools could not be used due to low bandwidth capacities and server problems. Instead, a mobile classroom had to be implemented by pair-wise connection of laptops. These laptop pairs allowed for access to the learning games by connecting to several local servers but not for access to the online databank server. Thus, it was only a temporary solution to the implementation problems.

Apart from these technical issues, there were also psychological points, which deserve consideration. First of all, lack of understanding the concept and content of some learning games reduced the motivation of players. Consequently, children had to be supported and guided through the learning games by experimenters. In further developments of the learning platform, this fact needs to be considered to ensure that such non- or misunderstanding does not prevent participants from playing and enjoying the games. One might think of a practice phase before starting the respective game. Second, with respect to motivational aspects, pair-wise matching of children performing comparably well turned out to be effective to maintain motivation and keep children playing the games [14]. As the advantages of adaptive testing have widely been discussed [39-40], the current results encourage us to pursue the implementation of intra- and inter-individual adaptivity of the learning games and the platform.

4 Advancing the Web-based Learning Platform: Introducing Adaptivity

In a next version of the web-based learning platform, adaptivity will be realized to adjust the difficulty of arithmetic and orthographic games both intra- and inter-individually.

At an intra-individual level, game behavior will be adapted according to a player's individual performance. First, this kind of adaptivity is needed for an individually tailored initial assessment of the students' performance which is used to set a start value for task difficulty as well as to monitor learning progress. Second, it is necessary for games with computer-controlled opponents. Based on the players' previous performance the activity of the computer-controlled player shall be adapted to allow for an individual success rate of at least 50%.

At an inter-individual level, game behavior is modified with respect to a player's performance relative to (1) her/his current opponent and (2) the set of all registered players. This kind of adaptivity can be implemented in two ways: On the one hand, individual log data, for instance test scores from the initial assessment as well as from recent playing sessions, can be used to provide an index of competency (like an ELO score in chess, [41]). Such a competency index allows for matching students with a comparable competency level. On the other hand, handicaps can be specified for the better performing student in a pair of players. Such handicaps can be realized via time-delays in item presentation or answer registration for the better performing student. Thereby, it is possible to balance success rates and keep the motivation of the individual players high regardless of their skill level. Currently, intra-individual adaptivity in the web platform has already been modelled by means of Item-Response Theory (IRT).

This requires to identify relevant competencies and to model them based on IRT-models as state-of-the-art methodology [42-43]. Therefore, a rich item set was analyzed and numerical/spelling errors were evaluated with respect to individual arithmetic/orthographic markers. Moreover, item parameters (difficulty and discrimination) according to the Birnbaum model [44] were derived for each arithmetic operation (addition, subtraction, multiplication, etc.) and orthographic rule (capitalization, gemination, lengthening, etc.). These parameters are crucial to choosing the most appropriate next item in the assessment or training and to adjust task difficulty to the individual players' competence levels. In spelling, several orthographic rules can be applied to a single word. A word can be difficult according to one spelling rule, but comparatively easy with respect to another rule. On the other hand, players may be mastering one spelling rule, but not another one. Therefore, adaptivity in our web-platform does not refer to some overall difficulty of an item, but to the specific difficulty of an item attribute, which will be selected corresponding to the player's specific capability.

As groundwork for adaptive intervention, an initial adaptive assessment for arithmetic and orthography was implemented as follows: Its starting point is information about an individual's current state (via, e.g., a likelihood function on the possible states). This information is exploited to select an appropriate item to be presented next. After observing and evaluating the individual's response the plausibility function is updated. For spelling, a key functionality of any assessment and intervention is the automatic evaluation of open format responses. It needs to be decided automatically whether a typed in word is spelled correctly or incorrectly with respect to a particular orthographic marker. Efficient pattern matching algorithms were applied to online evaluate correctness of spelling. Fig. 2 presents a schematic illustration of the adaptive procedure during the initial assessment (A) and the update of the person ability estimate after each trial (B).

This adaptive procedure reduces assessment time but – more importantly – allows customizing subsequent intervention to individual needs by adjusting the difficulty level of learning games and/or the competency level of competitors.

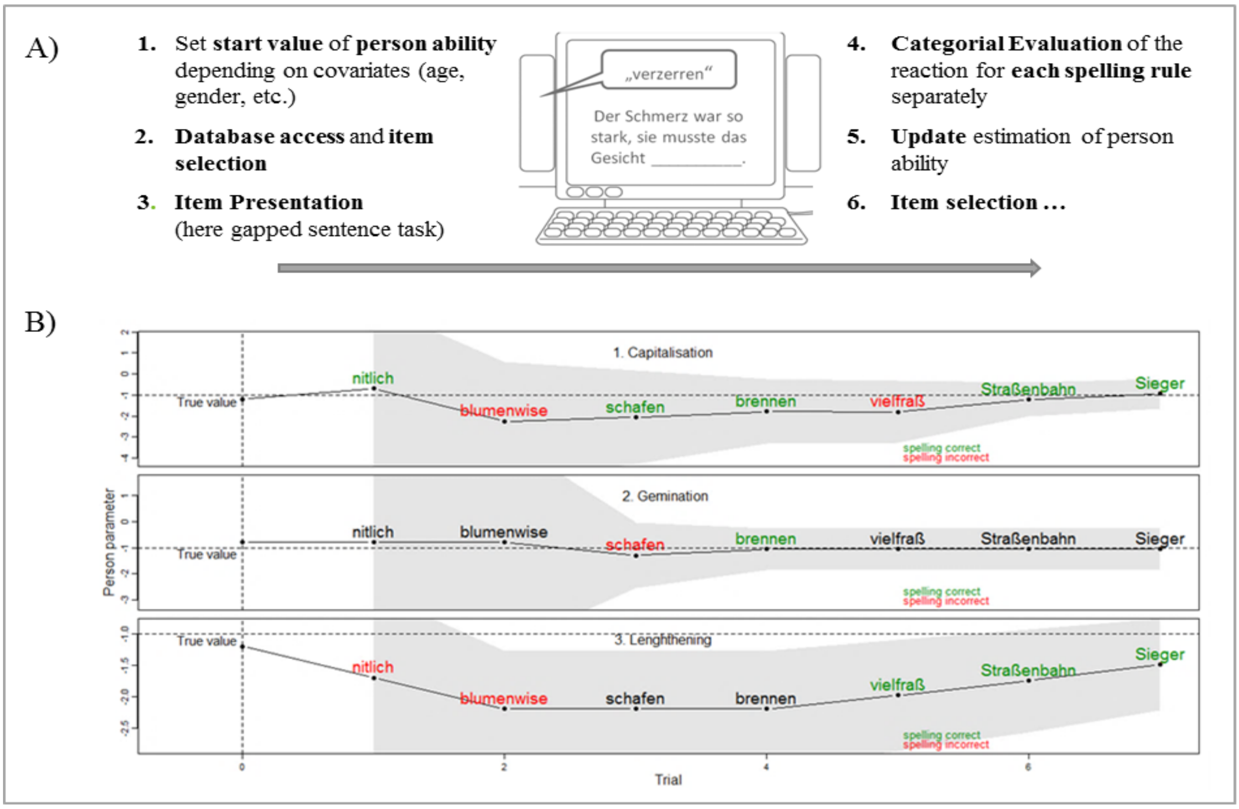

Fig. 2 A) Procedure of the initial intra-individual assessment. B) Simultaneous update of the person's three rule-specific ability parameters within an adaptive procedure during the initial assessment indication estimation.

Thus, it provides the basis for i) further inter-individual adaptive procedures, which is the next steps to be implemented, and ii) the evaluation of the efficiency and effectiveness of such adaptive procedures in informal learning as compared to non-adaptive procedures.

5 Conclusion and Perspective

The current project presents an interdisciplinary approach on developing an interactive web-based learning platform for arithmetic and spelling. The respective platform was developed considering latest theoretical and methodological developments in the domain of educational psychology, numeracy and literacy research. Results of the first evaluation of the web-based learning platform were consistent with previous studies showing that computer-supported learning environments are well able to corroborate numeracy and literacy skills and mitigate respective deficits [45-46]. We obtained general (numeracy) and differential (orthography) learning effects. Nevertheless, we also encountered complications due to technical issues when testing the platform in the field, such as for instance low band-width in schools. A possible solution to this issue might be to consider server-push-based communication models [47], where the central server initiates the request for a next transaction.

However, the evaluation also revealed that pairing students performing comparably well is inevitably necessary to keep participants motivated [14]. Automated selection of balanced opponents can be ensured in the future by implementing computerized adaptive procedures. Intra- and inter-individual adaptivity not only reduce assessment time but - more importantly – also allow for customizing subsequent intervention to the specific individual's needs. Future developments of the web-based learning platform will focus on implementing adaptivity, the extension to other age and at-risk groups like children with dyslexia and dyscalculia and a thorough scientific evaluation of the platform. Hereby, we want to apply both behavioral and neuroscientific methods to better understand children's learning process and thereby extend the educational neuroscience approach to serious games. We are confident that with these measures, we will develop a web-based learning platform, which successfully complements formal learning by informal learning games accessible almost anywhere via (mobile) internet.

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