ADAPTING STRATEGY CHOICES TO SITUATIONAL FACTORS: THE EFFECT OF TIME PRESSURE ON CHILDREN'S NUMEROSITY JUDGEMENT STRATEGIES

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The present study investigated the effect of time pressure on 6th graders' (11-12 years old) numerosity judgement strategies under three different time pressure conditions. Time pressure was manipulated by varying the maximum presentation time of the stimuli on three different levels: 5 s in the severe, 10 s in the moderate, and 20 s in the low time pressure condition. Analysis of the results in terms of the theoretical framework of Lemaire and Siegler (1995) revealed an effect of increasing time pressure on several parameters of strategy use such as participants' strategy repertoire, relative frequency of strategy use and efficiency of strategy execution. Unexpectedly, we did not observe a significant decline in the adaptiveness of strategy choices as a function of item characteristics. Taken as a whole, these results indicate that children are already at a young age able to adapt their strategy use to the external demands of a task.

Recent studies have shown that people know and use several strategies to accomplish most cognitive tasks (for an overview, see Siegler, 1996). This strategic variability has been observed in different domains, such as simple addition (Siegler & Robinson, 1982), subtraction (Siegler, 1987), scientific reasoning (Kuhn & Phelps, 1982), time telling (Siegler & McGilly, 1989), serial recall (McGilly & Siegler, 1990), and spelling (Rittle-Johnson & Siegler, 1999). An important consequence of this strategic variability is that, for each item in the task, the individual is faced with the challenge of choosing a strategy that is most adaptive for the given item.

Payne, Bettman, and Johnson (1993) assume that several factors affect an individual's strategy choice. A first factor involves the characteristics of the different strategies that are at hand for an individual. Strategies can differ in the amount of cognitive effort required to execute them, but also in their accuracy. A second factor concerns subject characteristics, such as limitations in cognitive resources as well as the level of expertise in a specific task.

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domain. Third, contextual factors can influence which strategies will be employed. In this respect, Reder (1987, 1988) distinguishes between intrinsic factors or cues in the task, such as the exact nature and sequence of the different items in the task and extrinsic factors or cues in the situation, such as the time available to give a response.

The three factors mentioned above are assumed to interact with each other when a subject makes an adaptive strategy choice. Different contexts have different properties that affect the relative advantages and disadvantages of the various strategies. Moreover, the characteristics of the context can interact with the cognitive resources of the individual to execute various strategies effectively in that context. In sum, a given strategy can be regarded as relatively more effective than other strategies in one context and relatively less effective than these same strategies in another context.

The adaptation of strategy choices to contextual variations has already been investigated in many studies covering a wide array of task domains. Among the types of contextual variables that have already been studied are the demands on cognitive resources (e.g., Klayman, 1985; Payne et al, 1993), the need to balance considerations of speed and accuracy (e.g., Brent & Routh, 1978; Gardner & Rogoff, 1990), the requirement to adapt to immediate or long-term goals (e.g., Crowley & Siegler, 1993; Payne, Bettman, & Johnson, 1988; Siegler, 1987), and the base rate with which different types of problems are presented (e.g., Lemaire & Reder, 1999; Lovett & Anderson, 1996; Reder, 1987; Schunn & Reder, 2001).

Somewhat surprisingly, little attention has been given to time as a contextual factor in the domain of strategy selection, notwithstanding the fact that many human actions are taken under time limits. The few studies investigating the effect of time constraints on people's strategy use have been almost exclusively carried out in the domain of decision making, mostly with adult participants. A standard research method in this area involves presenting different response alternatives that vary in their values along several dimensions and whereby participants are asked to choose the best alternative. In their overview of the literature in this domain, Svenson and Maule (1993) indicate that there are systematic changes in cognitive processing when participants have to make decisions under time pressure. As demonstrated by Miller (1960) and Payne et al. (1988), individuals can adapt in several ways to an increase in time restrictions. As a first type of adaptation, the individual can accelerate the processing of information, or, in other words, speed up the execution of the current strategy. Second, there can be an increased selectivity in the information input being processed. In this case, the individual will apply the same strategy in a more sketchy way by filtering out some parts of the present information. A final way to cope with increased time constraints is by selecting and applying a different strategy. According to the theoretical
framework of Payne et al. (1993), time constraints are assumed to alter an individual's strategy choices once the preferred strategy for a particular choice/benefit combination cannot be implemented in the time allowed. As a consequence, the individual adapts to the time constraints by adopting the best strategy that is available in the strategy repertoire to comply with the situational restrictions.

Starting from the above-mentioned pieces of theoretical account and empirical evidence of the impact of time pressure on individuals' strategy choices, we investigated the effect of this variable on strategy choices in another task domain than decision making and with children as participants instead of adults. More specifically, we examined if, and in which ways, children would adapt their strategy choices to different levels of time pressure in the context of a numerosity judgement task. Previous studies by Luwel, Verschaffel, Onghena, and De Corte (2003a, 2003b), have shown that the task of judging different numerosities of blocks presented in a grid was particularly useful for investigating adaptations in strategy use to extrinsic task characteristics. More specifically, in one study Luwel et al. (2003a) manipulated the shape of the grid wherein the blocks were presented, whereas in the other study (Luwel et al., 2003b) the variety of grid sizes was varied.

These authors have shown that an adaptation in strategy choices can be characterized as an alteration in one or more of the four dimensions of strategic competence that are distinguished in the theoretical framework of Lemaire and Siegler (1995). These four dimensions refer to: (a) the repertoire of strategies that people use, (b) the relative frequency with which each strategy is applied, (c) the efficiency with which each strategy is executed, typically measured in terms of speed and/or accuracy, and (d) the adaptiveness with which the different strategies are chosen and applied on a given set of items. In line with Reder's (1987, 1988) distinction between intrinsic and extrinsic task factors, this latter type of adaptiveness can be labeled as "intrinsic adaptiveness", whereas the adaptation of strategy choices to varying levels of time pressure can be considered as "extrinsic adaptiveness".

Whereas in the previous studies of Luwel et al. (2003a, 2003b) the experimental manipulations led to an alteration in only one of the four dimensions of Lemaire and Siegler's (1995) framework—namely the relative frequency with which the different numerosity judgements were applied—, we expected in the present study, based on the previous work on time pressure (e.g., Miller, 1960, Payne et al., 1988), a change in all dimensions of Lemaire and Siegler's (1995) theoretical framework.
Basic Paradigm

The basic paradigm in the present study involved judging different numerosities of blocks that were presented in a square 10 x 10 grid. Previous studies (Luwel, Verschaffel, Onghena, & De Corte, 2000, 2001; Verschaffel, De Corte, Lamote, & Dherdt, 1998) assumed that people use in general three different numerosity judgement strategies to accomplish this task, depending on the ratio of blocks to empty squares in the grid. When there are few blocks and many empty squares, the addition strategy will be used. When applying this strategy, the blocks in the grid can be counted one by one, or the given quantity of blocks can be divided into a number of subgroups (whereby the numerosity of blocks in each subgroup can be determined by subitizing them when there are no more than four blocks in the subgroup, by counting them in chunks of two or more blocks, or by estimating them), and the judged numerosities of the different subgroups are added. When there are many blocks and few empty squares, people can apply the subtraction strategy in which the number of empty squares is determined (by means of an addition strategy) and subtracted from the total number of squares in the grid. When there are too many blocks and too many empty squares to be determined relatively precisely within the given time limit, people are assumed to fall back on the estimation strategy whereby the numerosity of blocks is determined in a relatively quick but imprecise way on the basis of a rough and global inspection of the stimulus material.

Each of these three strategies is expected to elicit a specific pattern of response times (and deviation scores) as a function of the numerosity of blocks present in the grid. The application of the addition strategy is assumed to lead to linearly increasing response times (and deviation scores) with an increasing numerosity of blocks. Indeed, the more blocks in the grid, the more time that is required to determine their numerosity. The use of the subtraction strategy, on the contrary, is assumed to lead to linearly decreasing response times (and deviation scores) with an increasing numerosity of blocks. The more blocks that are present in the grid, the less empty squares that need to be determined and, thus, the less time is needed to execute the subtraction strategy. Due to its nature, the employment of the estimation strategy is expected to elicit relatively quick response times (and relatively large deviation scores) that are not seriously affected by the given numerosity of blocks. Starting from these properties of the three basic kinds of strategies, we constructed four hypothetical response-time patterns reflecting different combinations of these three strategies for the range of numerosities addressed in the task (see Figure 1).

Graph a describes the hypothetical response-time pattern that is assumed to occur when solely the addition strategy is applied (=Pattern 1). Graph b
shows the hypothetical response-time pattern for the combined and adaptive use of the addition and estimation strategy (=Pattern 2). In this pattern, it is assumed that subjects will apply the addition strategy on the trials with few blocks and many empty squares. However, when there are too many blocks to allow accurate counting (within the given time limit), participants can resort to the estimation strategy. Graph c contains the hypothetical pattern of response times that is supposed to occur as a result of the combined and adaptive application of the addition and subtraction strategy (=Pattern 3). For Pattern 3, subjects will supposedly apply the addition strategy on the trials with few blocks and many empty squares and use the subtraction strategy on the trials with many blocks and few empty squares. Graph d shows the response-time pattern that is assumed to appear when all three numerosity judgement strategies are applied adaptively (=Pattern 4).
Hypotheses and Predictions

Time pressure in the present study was operationalized by manipulating the maximum presentation time of the stimuli. This resulted in three conditions, each with a different maximum presentation time: a severe (5 s), a moderate (10 s) and a low (20 s) time pressure condition. The study by Verschaffel et al. (1998) had shown that, when being asked to determine the 100 possible numerosities in a 10 x 10 grid with a maximum presentation time of 20 s, sixth graders rarely were unable to answer within the given time interval. Therefore, we were quite confident that participants of the same age group would experience little time pressure when judging numerosities presented in the same grid in the 20 s-condition. Based on the cost/benefit framework of Payne et al. (1993) and on the literature regarding time pressure in decision making tasks (Miller, 1960; Payne et al., 1988; Svenson & Maule, 1993), we expected the following effect of time pressure on the four different dimensions of strategic competence distinguished in the model of Lemaire and Siegler (1995).

For the first dimension, the strategy repertoire, we expected that all sixth graders in the present study would fit with Pattern 3 or 4 (= Hypothesis 1). Indeed, previous studies (Luwel et al., 2000; Luwel, Verschaffel et al., 2001; Verschaffel et al., 1998) had demonstrated that the subtraction strategy is very common among sixth graders. In addition, we hypothesized an effect of time pressure on the presence of the estimation strategy (= Hypothesis 2). More specifically, with increasing time pressure, we predicted a significant decrease in the number of participants that would solely use the addition and the subtraction strategy (i.e., fitting Pattern 3) and a significant increase in the number of participants that would apply the estimation strategy next to the addition and subtraction strategy (i.e., fitting Pattern 4). This prediction was based on the assumption that with increasing time constraints, participants will not have sufficient time to apply the more accurate, but at the same time more time-consuming, addition and subtraction strategies on the items in the middle range of the numerosity dimension. As a consequence, they will have to resort to the less accurate but faster estimation strategy for solving that type of items.

Based on the same assumption, we also hypothesized a change in the relative frequencies of strategy use (= Hypothesis 3). More specifically, we predicted, with increasing time pressure, a significant decrease in the number of trials on which participants would use the addition and subtraction strategies and a significant increase in the number of trials on which the estimation strategy would be applied.

The third dimension, the efficiency of strategy use can be measured on two different variables, namely speed and accuracy (Lemaire & Siegler, 1995). Regarding the speed of strategy execution, we hypothesized an increase in
the speed of the addition and subtraction strategy with increasing time pressure (Hypothesis 4). This hypothesis was based on the assumption that the less time one has to apply a strategy on a given item, the faster its execution, as was evidenced in the studies of Miller (1960) and Payne et al. (1988). However, since we assumed that, by its nature, the execution time of the estimation procedure would always be very fast and more or less the same, regardless of the time available, we did not expect an effect of time pressure on the speed of the estimation strategy (Hypothesis 5). Based on the same assumption, we also expected that, in all conditions, the mean response time of the estimation strategy would be lower than the one of the addition and subtraction strategies (Hypothesis 6).

The following hypotheses were made with respect to strategy accuracy. First, we expected a significant decrease in the accuracy of the addition and subtraction strategy with increasing time pressure (Hypothesis 7). This hypothesis was based on the assumption that the less time participants have to determine a given numerosity, the faster and, thus, the less accurate they will execute their strategies. The estimation strategy is assumed to lead to considerably less accurate answers, which would be only marginally affected by time pressure. Therefore, we expected no difference in the mean accuracy of the estimation strategy among the three different conditions (Hypothesis 8). Finally, we hypothesized that the estimation strategy would be significantly less accurate than the addition and subtraction strategy in all three conditions, whereas, based on the results of previous studies (Luwel et al., 2000; Luwel, Verschaffel et al., 2001), we did not expect a difference in accuracy between the addition and subtraction strategy (Hypothesis 9).

Finally, we expected a decrease in the adaptiveness with which the different strategies were applied to the items in the task with increasing time pressure (i.e., the intrinsic adaptiveness) (Hypothesis 10). This hypothesis was based on the assumption that the less time available to solve a task, the more difficult it will be to select the most suitable strategy, resulting in less adaptive strategy choices.

Method

Participants

Eighty-one sixth graders (11-12 years old), coming from four classes in two schools, were involved in the experiment. Participants were matched on mathematical ability across conditions on the basis of their overall results for mathematics during the last year. Both sexes were about equally represented in each condition.
Materials

The task was presented to the participants using an IBM-compatible computer equipped with a Pentium III-processor and a 15'' monitor with a resolution set to 800 x 600 pixels. Participants were seated at about 50 cm from the computer screen. Stimuli were square grids consisting of 10 x 10 little square units. These square units could either be “on” (i.e., filled with a green-colored block) or “off” (i.e., empty, and thus having the same black color as the background of the whole screen). Each square had a size of 1 x 1 cm. A small black line separated the green squares, whereas the empty squares were not bounded. The outline of the square grid was visible and was colored red.

Procedure

The experiment consisted of three conditions: a severe, a moderate and a low time pressure condition. Participants were randomly assigned to one of the three conditions and were tested individually. In each condition, they were presented all possible numerosities of blocks from the 10 x 10 grid (i.e., ranging from 1 to 100 blocks). The maximum presentation duration of the stimuli was 5 s in the severe time pressure condition, 10 s in the moderate time pressure condition, and 20 s in the low time pressure condition. For each participant, the sequence of the stimuli as well as the placement of the blocks within the grid was randomized by the computer. After each trial, the computer recorded participants’ response and response time (with an exactitude of 0.1 s). The response time corresponds to the time between the moment when the stimulus appeared on the computer screen and the moment the participant began to express the answer (as determined by a key pressure by the experimenter). To minimize possible fatigue effects, participants were given a brief pause after every 25 trials.

At the beginning of the experiment, participants were told that a large number of displays would be presented on the computer screen, each showing a grid with a different number of green blocks. Participants were asked to determine the number of green blocks in each grid as accurately as possible within the respective time constraint of 5, 10, or 20 s. Before the start of the actual experiment, participants were given 3 example trials they had to solve within the time constraints of the respective condition they had been assigned to. These example trials were representative for the whole continuum of blocks in the grid (i.e., 3, 48, and 95 blocks). During these example trials, participants received immediate feedback about the accuracy of their answer: a message appeared on the screen telling them whether their response was considered as an accurate or as an inaccurate numerosity
judgement. A 10% deviation criterion was used to decide whether a numerosity judgement was considered accurate or not. However, this feedback was dropped as soon as the actual experiment started. The purpose of these example trials was twofold: (a) to help the children to get accustomed to the task and the time constraints under which they had solve the different items, and (b) to allow them to determine the total number of squares in the grid before the actual start of the experimental data collection.

Participants were asked to verbally state their answer as soon as they knew it. The experimenter then immediately pressed a key that stopped the computer timer and emptied the grid. After the response was typed in by the experimenter, a new stimulus appeared on the screen. When no response was given within the given time constraint, the screen went blank and the participant was asked to make a numerosity judgement anyhow.¹

Data-analysis

Before reporting the results with respect to the different dimensions of strategic competence, we describe the procedure for strategy identification that was used in the present study. Children’s strategies as well as the range of their application was identified by fitting their actual response-time patterns with the hypothetical response-time patterns as shown in Figure 1. Three different regression models were used for that purpose: the simple linear model, the two-phase segmented linear regression model (Beem, 1993, 1995), and the three-phase segmented linear regression model (Beem, 1999). In the well-known linear models, the relationship between the independent and the dependent variable is described by one linear regression equation. The two-phase segmented linear regression model looks for a "break" or "change point" in the data and accordingly computes two regression equations, which hold for different ranges of the independent variable. The two-phase segmented model can be formally described as:

\[ Y = a_1 + b_1 x + e \quad (x \leq s) \]  
\[ Y = a_2 + b_2 x + e \quad (x > s) \]

where \( x \) is the independent and \( y \) is the dependent variable, the parameters \( a_i \) and \( b_i \) (\( i = 1,2 \)) denote respectively the intercept and the slope of the regres-

¹ Although, the screen went blank, the clock only stopped after participants had given the answer. In this way, it was prevented that a lot of response times in the middle range would have the same value of e.g., 5 s in the case of the severe time pressure condition, which would have disturbed our analyses with the segmented regression models (see further).
sion lines and $e$ is the error term. The parameter $s$ is called the \"change point\" or \"break point\". For values of the independent variable up to $s$ the first regression equation is fitted, while for values larger than $s$ the second equation—with a different intercept and slope—holds. The program simultaneously estimates the regression parameters and change point using a least squares algorithm that always finds the optimal solution.

The three-phase segmented linear regression model is an extension of the two-phase segmented linear regression model in which the relationship between the independent and the dependent variable is described by three regression equations instead of two. Completely analogous to the two-phase segmented model, the three-phase segmented model computes three different regression equations and estimates two change points, namely $s_1$ and $s_2$. This model has the following formal description:

\begin{align}
Y &= a_1 + b_1 x + e \ (x \leq s_1) \quad (3) \\
Y &= a_2 + b_2 x + e \ (s_1 < x \leq s_2) \quad (4) \\
Y &= a_3 + b_3 x + e \ (x > s_2) \quad (5)
\end{align}

The two- and three-phase segmented linear regression models are less well known and used, although they are, according to Beem (1993, 1995, 1999; Ippel & Beem, 1987), ideally suited for the study of strategy shifts like those involved in the present study. Indeed, the change points that are computed by both segmented linear regression models identify the trial on which one strategy is replaced by the other. Consequently, this procedure enables an identification of the different strategies based on their specific properties as well as a determination of their range of application. The four hypothetical response-time patterns from Figure 1 can be defined in terms of the different parameters of the statistical models presented above. This leads to the following characterization of each pattern:

1. Pattern 1 (always addition): no change point, and the only $b$-parameter is positive.
2. Pattern 2 (first addition, then estimation): one change point, a positive $b$-parameter for the first regression line, and a $b_2$-parameter with a value close to zero.
3. Pattern 3 (first addition, then subtraction): one change point, a positive $b_1$-parameter and a negative $b_2$-parameter.
4. Pattern 4 (first addition, then estimation, and finally subtraction): two change points, a positive $b_1$-parameter, a $b_2$-parameter with a value close to zero, and a negative $b_3$-parameter.
The different strategies applied by an individual can be identified by fitting the individual response-time pattern with the different hypothetical response-time patterns by going through the following stepwise procedure. First, the three-phase segmented linear regression model is fitted to all individual response-time patterns. Next, the data are tested for the occurrence of two change points following the cusums method (Brown, Durban, & Evans, 1975; Schweder, 1975). When the cusum test has detected two change points in the individual response-time pattern, this data pattern is further tested for a possible fit with Pattern 4 by computing significance tests regarding the linear restrictions of the b-parameters from the different regression equations by using the F-type statistic (Beem, 1993, 1999). If no evidence is found for the presence of two change points, we assume that the subject did not apply three strategies. Next, the two-phase segmented linear regression model is fitted to the same data pattern and a cusum test for a single change point is executed. Response-time patterns that show one change point are further tested for a possible fit with Pattern 2 or 3. This is done again by computing significance tests regarding the linear restrictions of the b-parameters from the different regression equations on the basis of the F-type statistic. When we do not detect a change point at all, we assume that the response-time pattern of that particular subject is similar to Pattern 1 and, thus, that only the addition strategy is used. A more detailed account of this procedure can be found in Luwel, Beem, Onghena, and Verschaffel (2001). The studies of Luwel, et al. (2000); Luwel, Verschaffel et al. (2001) and Verschaffel et al. (1998) demonstrated the value of Beem’s (1993, 1999) segmented linear regression models for detecting participants’ strategy use in cognitive tasks like the numerosity judgement task used in the present study.

Results

In a first section, we present the results regarding the effect of time pressure on the overall speed and the overall accuracy of participants’ responses. Next, we describe the results for each of the four dimensions of strategic competence that are distinguished in the framework of Lemaire and Siegler (1995). Unless stated otherwise, an alpha level of .05 was used for all statistical tests. Exact p-values will be reported, but very small values are round-
ed to $p < .0001$. The control variable of sex did not have an effect on any of the dependent variables. Therefore, this variable was left out of the analyses.²

**Effects of Time Pressure on Overall Performance**

To assess the effect of our manipulation on participants’ overall performance, we conducted two one-way analyses of variance with condition (low, moderate, and severe time pressure) as independent between-subjects variable and, respectively, response time and deviation score as dependent variables. The deviation score reflects the absolute difference between the actual numerosity of blocks in a given trial and a participant’s response for that trial. For instance, a subject who responded with “30” or “40” to a numerosity of 35 blocks obtained a deviation score of 5 for that particular trial.

With respect to speed, this analysis revealed a significant effect of time pressure, $F(2, 70) = 38.97$, $MSE = 4.58$, $p < .0001$. A posteriori Tukey tests indicated that the mean response time in the low time pressure condition ($M = 12.75$ s) was significantly larger than the mean response time in the moderate ($M = 9.55$ s) and the severe ($M = 7.44$ s, $p = .0001$) time pressure condition. Moreover, the mean response time of the moderate time pressure condition was significantly larger than the one of the severe time pressure condition ($p = .003$).

The analysis on the deviation scores showed a significant effect of condition, $F(2, 70) = 86.12$, $MSE = 1.32$, $p < .0001$. A posteriori Tukey tests

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² Before analyzing the data, two types of errors were removed (following the same principles as in the study of Luwel et al., 2000):

1. **Inverse errors**: These are errors that are due to the fact that—at the end of the numerosity judgement process—the participant has forgotten whether (s)he was engaged in an addition or subtraction strategy, leading to numerosity judgement errors approximating the number of empty squares instead of the actual numerosity of the blocks. To be classified as an inverse error, the following three conditions had to be fulfilled (a) the response deviates at least two standard deviations from the subject’s mean deviation score for all trials in a specific grid, (b) the response fits the so-called complement rule, stating that the sum of the subject’s response and the actual numerosity of blocks in the trial must equal the total number of squares in the grid $\pm 5$ (or $\pm 10$ when the response deviates at least three standard deviations from the subject’s mean deviation score), (c) inverse errors are assumed to occur solely in the first and last third of the trials when ordered according to the number of blocks.

2. **Typing errors**: These are extreme errors that were the result of a typing error by the experimenter (e.g., 488 instead of 48). All numerosity judgement errors that had a minimal absolute deviation of 90 from the number of presented blocks were considered as typing errors. Furthermore, we removed all cases wherein the participants had not made any numerosity judgement at all.

Based upon these two criteria, 23 errors (18 inverse errors and 5 typing errors) were removed from a total of 2352 data points (i.e., 1%).
revealed that the mean deviation score in the low time pressure condition \((M = 2.03)\) was significantly lower than the mean deviation score in the moderate \((M = 4.21)\) and the severe \((M = 6.30)\) time pressure condition. In addition, the mean deviation score in the moderate time pressure condition was significantly lower than the one in the severe time pressure condition (all \(p < .0001\)).

To summarize: our manipulation of time pressure had the expected effect on participants’ overall performance. With increasing time pressure, we observed an increase in participants’ overall speed and a decrease of their overall accuracy.

**Strategy Repertoire**

According to Hypothesis 1, all participants were expected to fit with Pattern 3 or Pattern 4. Hypothesis 2 stated that, with increasing time pressure, there would be an increase in the number of participants with a response-time pattern that would fit Pattern 4 (i.e., using the estimation strategy next to the addition and subtraction strategy) and a decrease in the number of participants with a response-time pattern fitting Pattern 3 (i.e., applying the addition and subtraction strategy).

Subjects’ strategies were assessed according to the above-mentioned step-wise procedure with the segmented linear regression models. This analysis revealed that the majority of participants in each condition showed a fit with one of the four hypothetical response-time patterns (i.e., 93% in the low and severe time pressure condition and 85% in the moderate time pressure condition). As expected, the children either fitted Pattern 3 (i.e., using the addition and subtraction strategy) or Pattern 4 (i.e., applying the addition, subtraction and estimation strategy). This finding is in line with what was found in previous studies where the response-time patterns of the majority of the children of this age did not fit either Pattern 1 or 2 (none of which involves the subtraction strategy. The mean adjusted \(R^2\) ‘s for participants fitting Pattern 3 were, respectively, .661, .767, and .868 for the severe, moderate and low time pressure condition, whereas, for participants fitting Pattern 4, these values were, respectively, .580, .712, and .653. Participants' distribution over the different hypothetical response-time patterns is shown in Table 1.

In a first Chi-square analysis, we tested whether there was a difference among conditions in the distribution of participants across the different hypothetical response-time patterns. This analysis showed a significant difference among conditions, \(\chi^2(4, N = 81) = 28.49, p < .0001\). The data in Table 1 suggest that this difference is located in the low time pressure condition. Therefore, we conducted two additional Chi-square analyses. In the first
additional analysis, we tested whether there was a difference in the distribution of participants between the severe and the moderate time pressure condition. This analysis did not reveal such a difference. Therefore, we grouped the data of these two conditions and tested in a second additional analysis whether there was a difference in the distribution of participants between the low time pressure condition and the grouped data from the moderate and severe time pressure condition. This analysis revealed that there were significantly more participants fitting Pattern 3 and significantly less participants fitting Pattern 4 in the low time pressure condition than in the other two conditions, $\chi^2(2, N = 81) = 27.00, p < .0001$.

Relative Frequency of Strategy Use

We hypothesized that more time pressure would result in an increase in the application of the less accurate estimation strategy and, accordingly, in a decrease in the use of the more accurate addition and subtraction strategies (= Hypothesis 3). To test this hypothesis, we compared the frequency of use of each strategy on the whole range of items among the different conditions.

The relative frequency of use of each strategy was derived from the location of the change points that were computed by the segmented linear regression models. For participants fitting Pattern 3, the frequency of use of the addition strategy was derived from the number of trials located before the change point, whereas the frequency of use of the subtraction strategy was based on the number of trials located after the change point. For participants fitting Pattern 4, the frequency of use of the addition strategy was derived from the number of trials located before the first change point, the frequency of use of the estimation strategy was based on the number of trials situated between both change points, and the frequency of use of the subtraction strategy was derived from the number of trials located after the second change point. For example, a participant with a first change point located on 40 and a second change point located on 75 was assumed to have used the
addition strategy on 40% of the trials, the subtraction strategy on (100 - 75 =) 25% of the trials and the estimation strategy on (75 - 40 =) 35% of the trials.

We conducted for each strategy a one-way analysis of variance with condition (low, moderate and severe time pressure) as independent between-subjects variable and frequency of strategy use as dependent variable. For the addition strategy, this analysis revealed a significant effect of condition, \( F(2, 70) = 23.90, MSE = 115.61, p < .0001 \). A posteriori Tukey tests indicated that the addition strategy was significantly more applied in the low time pressure condition \( (M = 51.76\%) \) than in the moderate \( (M = 40.61\%, p = .002) \) and the severe \( (M = 30.76\%, p = .0001) \) time pressure condition. Moreover, the addition strategy was used significantly more frequently in the moderate than in the severe time pressure condition \( (p = .006) \). We also observed a significant effect of condition on the frequency of use of the subtraction strategy, \( F(2, 70) = 9.33, MSE = 99.98, p = .0003 \). A posteriori Tukey tests revealed that the subtraction strategy was applied significantly more frequently in the low time pressure condition \( (M = 38.64\%) \) than in the moderate \( (M = 28.96\%, p = .004) \) and severe \( (M = 27.28\%, p = .0005) \) time pressure condition. Finally, we observed a significant effect of condition on the frequency of use of the estimation strategy, \( F(2, 70) = 24.22, MSE = 277.29, p < .0001 \). A posteriori Tukey tests showed that the estimation strategy was applied significantly less frequently in the low time pressure condition \( (M = 9.60\%) \) than in the moderate \( (M = 30.43\%, p = .0002) \) and severe \( (M = 41.96\%, p = .0001) \) time pres-

![Figure 2](image.png)

*Figure 2.* Frequency of strategy use as a function of the level of time pressure.
sure condition. The estimation strategy was also applied significantly less frequently in the moderate time pressure condition than in the severe time pressure condition ($p = .05$). Figure 4 shows the changes in relative frequency of strategy use for each of the three strategies under the three conditions.

**Efficiency of Strategy Use**

*Speed.* Following Hypothesis 4, an increase in time pressure was expected to result in a decrease in the response times of the addition and subtraction strategy, whereas the response times of the estimation strategy would not be affected by augmenting time restrictions (= Hypothesis 5). In Hypothesis 6, we stated that, in all conditions, the response times of the estimation strategy would be lower than those of the addition and subtraction strategies. Since not all participants had applied the estimation strategy, we could not conduct a standard two-way analysis of variance. Indeed, all participants for whom the segmented regression model did not detect three segments had no data with respect to the estimation strategy and would therefore be excluded from the analysis. Therefore, we decided to conduct two sets of analyses. In a first set, we ran three one-way analyses of covariance to investigate the effect of time pressure on the speed of each of the three strategies. In a second set, we compared the speed of the different strategies within each condition by means of a number of $t$-tests with a Bonferroni correction.

In the first set of analyses, average response time for each strategy was included as a dependent variable in a one-way analysis of covariance with condition as independent between-subjects variable. In order to control for a possible trade-off between accuracy and speed, we decided to include the deviation score (see further) as a covariate in these analyses. In line with our predictions, we observed a significant effect of time pressure on the speed of the addition an the subtraction strategy, $F(2, 69) = 81.59$, $MSE = 3.18$, $p < .0001$ for the addition strategy, and, $F(2, 69) = 42.07$, $MSE = 5.25$, $p < .0001$, for the subtraction strategy. A posteriori Tukey tests indicated that the mean response time of the addition strategy was significantly larger in the low time pressure condition ($M = 12.11$ s) than in the moderate ($M = 8.13$ s) and the severe time pressure condition ($M = 6.12$ s). Moreover, the mean response time of the addition strategy was significantly larger in the moderate than in the severe time pressure condition (all $ps < .001$). For the subtraction strategy, the a posteriori Tukey tests showed that the mean response time was significantly larger in the low time pressure condition ($M = 12.48$ s) than in the moderate ($M = 8.28$ s) and the severe ($M = 6.86$ s, all $ps = .0001$) time pressure condition.

Contrary to what was expected, we also observed a significant effect of
time pressure on the speed of the estimation strategy, $F(2, 45) = 5.67, MSE = 14.57, p = .006$. A posteriori Tukey tests revealed that the mean response time of the estimation strategy was significantly lower in the severe time pressure condition ($M = 8.44$ s) than in the moderate ($M = 11.86$ s, $p = .01$) and the low time pressure condition ($M = 14.58$ s, $p = .001$).

In a second set of analyses, we compared the speed of the three strategies within each condition by means of a number of $t$-tests for dependent samples. Contrary to our predictions, we observed that the estimation strategy was in all conditions, significantly slower than the addition strategy: $t(22) = 6.75, p < .0001$ for the severe time pressure condition, $t(18) = 7.10, p < .0001$ for the moderate time pressure condition and $t(6) = 2.68, p = .04$ for the low time pressure condition. The estimation strategy was also significantly slower than the subtraction strategy in the severe time pressure condition, $t(22) = 4.38, p = .0002$, and the moderate time pressure condition, $t(18) = 5.15, p < .0001$. For the low time pressure condition, we observed that the estimation strategy was only marginally significantly slower than the subtraction strategy ($p = .06$). Finally, the addition strategy was only significantly faster than the subtraction strategy in the severe time pressure condition, $t(24) = 2.31, p = .03$. The means and standard deviations of the response times for the different strategies and conditions in this set of analyses are shown in Table 2.

These results only confirmed our hypothesis regarding the effect of time pressure on the speed of the addition and subtraction strategy. Surprisingly, our predictions with respect to the estimation strategy were not confirmed: The supposedly fast estimation strategy turned out to be much slower than the addition and subtraction strategy and was unexpectedly seriously affected by the factor time pressure. These findings suggest that participants use (at least partially) a different kind of strategy than the estimation strategy—as it was conceived in our rational task analysis—on the items in the middle range of the numerosity continuum. Therefore, we will from now on use the term “other strategies” instead of “estimation strategy” when describing the results of the items in the middle range of the numerosity continuum. The incongruent findings with respect to the middle range will be interpreted in greater detail in the discussion section.

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Low</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addition</td>
<td>9.62 s (2.55)</td>
<td>7.58 s (1.61)</td>
<td>5.99 s (1.34)</td>
</tr>
<tr>
<td>Subtraction</td>
<td>12.48 s (3.62)</td>
<td>8.28 s (1.48)</td>
<td>6.86 s (2.07)</td>
</tr>
<tr>
<td>Estimation</td>
<td>14.58 s (6.82)</td>
<td>11.85 s (3.54)</td>
<td>8.44 s (2.62)</td>
</tr>
</tbody>
</table>
Accuracy For the second measure of strategy efficiency, namely accuracy, we predicted, with increasing time pressure, an increase in the mean deviation score of the addition and subtraction strategy (= Hypothesis 7), whereas the mean deviation score for the other strategies would not increase significantly (= Hypothesis 8). Furthermore, we hypothesized that, in each condition, the mean deviation score for the other strategies would be significantly larger than the mean deviation score of the addition and subtraction strategy, whereas there would be no significant difference in this score of the last two strategies (= Hypothesis 9). To test these predictions, the same two sets of analyses as for the response times were carried out, but this time the response time was entered as a covariate in the analyses of covariance.

This first set of analyses showed, as expected, a significant effect of time pressure on the accuracy of the addition and the subtraction strategy, $F(2, 69) = 12.95, \ MSE = 1.47, p < .0001$, for the addition strategy and, $F(2, 69) = 5.83, \ MSE = 2.83, p = .005$ for the subtraction strategy. A posteriori Tukey tests revealed that the mean deviation score of the addition strategy was significantly smaller in the low time pressure condition ($M = 1.10$) than in the moderate ($M = 1.94$) or the severe time pressure condition ($M = 1.91, ps = .05$). A second set of a posteriori Tukey tests indicated that the mean deviation score of the subtraction strategy in the severe time pressure condition ($M = 2.01$) was significantly larger than the mean deviation score in the moderate ($M = 1.61$) and the low time pressure condition ($M = 1.76, ps = .05$). As for the response times, we also observed an unexpected effect of time pressure on the accuracy of the other strategies, $F(2, 45) = 8.27, \ MSE = 8.03, p = .0009$. A posteriori Tukey tests indicated that the mean deviation score for the other strategies was significantly larger in the severe time pressure condition ($M = 11.90$) than in the moderate ($M = 8.56, p = .001$) or the low time pressure condition ($M = 7.05, p = .005$).

A second set of analyses showed that, as expected, the mean deviation score for the other strategies was significantly less accurate than the mean deviation score of the addition strategy in each of the three conditions: $t(22) = 16.05, p < .0001$, for the severe time pressure condition, $t(18) = 12.91, p < .0001$, for the moderate time pressure condition and, $t(6) = 5.44, p = .002$, for the low time pressure condition. Moreover, the mean deviation score for the other strategies was, as expected, significantly less accurate than the mean deviation score of the subtraction strategy in each of the three conditions: $t(22) = 15.35, p < .0001$, for the severe time pressure condition, $t(18) = 12.53, p < .0001$, for the moderate time pressure condition and, $t(6) = 4.21, p = .006$, for the low time pressure condition. Finally, the subtraction strategy was significantly less accurate than the addition strategy in the low time pressure condition, $t(24) = 2.50, p = .02$. The means and standard deviations of the deviation scores for the different ranges and conditions for this set of analyses are shown in Table 3.
Table 3. Means and Standard Deviations of the Deviation Scores for the Different Strategies as a Function of Level of Time Pressure

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Low</th>
<th>Moderate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addition</td>
<td>0.83 (0.66)</td>
<td>1.45 (1.59)</td>
<td>1.75 (1.08)</td>
</tr>
<tr>
<td>Subtraction</td>
<td>1.76 (1.12)</td>
<td>1.61 (1.76)</td>
<td>2.01 (2.53)</td>
</tr>
<tr>
<td>Other</td>
<td>7.05 (2.87)</td>
<td>8.56 (2.22)</td>
<td>11.89 (3.18)</td>
</tr>
</tbody>
</table>

The unexpected effect of time pressure on the accuracy measure for the items in the middle range, once again suggests that at least some participants used one or more alternative strategies next to the estimation strategy in this specific range of the numerosity continuum.

Adaptiveness. According to Hypothesis 10, we predicted a decrease in the intrinsic adaptiveness of strategy choices with increasing time pressure. In the present study, we were only able to analyze this adaptiveness on a group level by investigating to what extent participants were able to calibrate their strategy choices to item characteristics within each of the three experimental conditions (Siegler & Lemaire, 1997). Following our rational task analysis, one can assume that the addition strategy will be most frequently applied on the trials with few blocks and many empty squares, the subtraction strategy on the trials with many blocks and few empty squares, and one or more alternative strategies on the trials with many blocks and many empty squares. If this assumption is true, one can expect to find a significant negative correlation between the number of blocks and the frequency of use of the addition strategy on the one hand, and a significant positive correlation between these two variables for the subtraction strategy. Because of the nature of the alternative strategies, we did not expect a correlation between these variables.

For participants fitting Pattern 4, the following correlations were observed. In all three conditions, we found, as expected, significant negative correlations for the addition strategy: \( r(98) = -.90, -.89, \) and \( -.86, \) for, respectively, the low, moderate, and severe time pressure condition, all \( ps < .001. \) For the subtraction strategy, correlations were, in line with our predictions, significantly positive: \( r(98) = .87, .84, \) and \( .83 \) for, respectively, the low, moderate and severe time pressure condition for the subtraction strategy, all \( ps < .001. \) The correlations for the other strategies were, as predicted, non-significant in all conditions: \( r(98) = .17, .12, \) and \( .10. \) These results indicate that participants calibrated their strategy choices to the item characteristics. Contrary to our expectations, we did not observe a significant decrease in (intrinsic) adaptiveness with increasing time pressure, although there was a trend in the expected direction.
Discussion

In the present experiment we investigated the effect of time pressure on children's strategy choices when solving a numerosity judgement task. Time pressure was manipulated by varying the maximum presentation time of the numerosities among conditions. It was expected that participants would adapt their strategy use to the variations of this contextual variable and that this adaptation would manifest itself on the four dimensions of strategic competence distinguished by Lemaire and Siegler (1995). The analysis of results in terms of these authors' framework revealed the following changes in the four dimensions.

First, with respect to the strategy repertoire, the analysis of the response-time patterns revealed that, as expected, a vast majority of children applied the addition and subtraction strategy but that, with increasing time constraints, an increasingly larger number of participants also used one or more alternative strategies next to addition and subtraction strategy to solve the trials in the middle range of the numerosity continuum. This change in strategic repertoire was most apparent between the low and the moderate time pressure condition. This finding is consistent with findings from previous studies in which the size of the grid instead of maximum presentation time was manipulated as a situational factor (Luwel et al., 2000; Luwel, Verschaffel et al., 2001). These studies demonstrated a similar change in children's strategic repertoire when the size of the grid increased from 7 x 7 to 9 x 9 among conditions. As in the present study, children were not able to solve all the trials in the middle range by means of the addition or the subtraction strategy when the size of the grid exceeded their processing capacities.

Second, for the relative frequency with which the strategies were applied, we observed, in line with our predictions, a significant decrease in the use of the relatively accurate addition and subtraction strategies with augmenting time pressure and an increase in the application of a number of relatively less accurate alternative strategies for the trials on the middle range of the numerosity continuum. This finding was also in line with the results of the studies of Luwel et al. (2000) and Luwel, Verschaffel et al. (2001), showing that the larger the grid size, the greater the percentage of trials that could no longer be solved by means of either the addition or the subtraction strategy.

Third, the results regarding the efficiency of strategy execution confirmed our predictions only partially. First, we did observe the expected increase in the speed and the decrease in the accuracy of the addition and subtraction strategy with increasing time pressure. Second, and contrary to our predictions, we also observed an increase in processing speed and a decrease in accuracy for the items in the middle range with augmenting time restrictions. Third, the items in the middle range were unexpectedly solved much slower
than the items solved by means of the addition or the subtraction strategy. But, as expected, they were solved less accurately compared to the items that were solved by means of the last two strategies. As mentioned before, these findings suggest that at least a number of trials in the middle range were—at least for a number of participants—not always solved by the estimation strategy as conceived in our rational task analysis. A fourth finding with respect to the strategy efficiency was that the expected faster strategy execution of the addition strategy compared to the subtraction strategy was only observed in the severe time pressure condition.

Finally, for intrinsic adaptiveness, we observed relatively high adaptiveness scores for the addition and subtraction strategy but contrary to our predictions, there was only a very small non-significant decrease in the intrinsic adaptiveness with increasing time pressure. This suggests that children at the age of 11-12 years can already maintain a good intrinsic adaptiveness in their strategy choices, even under severe time pressure.

The findings of the present study with respect to the efficiency of strategy use for the items in the middle range seem to ask for a re-evaluation of the “estimation” component of our rational task analysis. According to this rational task analysis, items that cannot be solved by means of the relatively accurate and slow addition and subtraction strategy are addressed by means of an alternative strategy whereby the numerosity of blocks is determined in a relatively quick but imprecise way on the basis of a rough and global inspection of the stimulus material. This strategy is characterized by relatively low response times (which are not significantly influenced by the actual numerosity to be determined) and with large deviation scores. We have labeled this strategy as the “estimation strategy”. A visual inspection of the individual response time patterns shows, for most participants, a cloud of data points in the middle range consisting of a mixture of very small response times (suggesting the application of the “estimation strategy” as characterized above) and very large response times (suggesting the use of a special instance of the addition and subtraction strategy or one or more alternative strategies). An example of such an individual response-time pattern is exhibited in Figure 3. The unexpectedly high response times observed in the present study suggest that at least one other strategy than this estimation strategy was applied by at least some participants on at least some of the trials in the middle range.

One plausible alternative strategy could be the application of the addition or subtraction strategy followed by the use of the estimation strategy (i.e., the addition/subtraction + estimation strategy). When applying this strategy, participants start to execute the addition or the subtraction strategy until they have reached the limit of stimulus presentation time. Since the stimulus has disappeared and participants have not finalized the execution of the addition
or subtraction strategy yet, they will make their final numerosity judgement by adding an estimate of the remaining number of units to the already determined units (followed by subtracting the determined number of empty squares from the total number of blocks in the grid in the case of the subtraction strategy). This type of strategy has also been documented in a study by Brade (2003) in which children of different age groups were instructed to estimate numerosities that were shown to them on cards during 2 s. Brade noted that some pupils immediately started to count the number of objects on each card and that they increased their numerosity judgement with their estimation of the remaining number of objects on the card. However, the same study also bore evidence for the estimation strategy as it was conceived in our rational task analysis. Brade speaks in this context of “scanning with intuitive classification” and she describes it as “a fast scanning process that yields an estimate based on an intuitive quantification process” (p. 6). The occurrence of this alternative strategy, which can be characterized as a combination of an addition or subtraction with an estimation strategy, can account for the effect of time pressure on the response times and the deviation scores in the middle range of the numerosity continuum. Indeed, with a decrease in time pressure applicants of this addition/subtraction + estimation strategy can apply the addition or subtraction strategy on the items in the middle range for a longer time before switching to the estimation strategy, resulting in larger response times and more accurate answers for this segment.

Next to the addition/subtraction + estimation strategy, other strategies can also account for the effect of time pressure on the response times and the deviation scores in the middle range of the numerosity continuum. One such
alternative could be the application of a special instance of the addition or the subtraction strategy on the numerosities in the middle range, the so-called "rough addition/subtraction strategy". When participants notice that they cannot cope with the given time restrictions for the items in the middle range when applying the addition or subtraction strategy in a normal fashion (i.e., by counting the units one by one or by determining the units in very small groups), they can switch to a more imprecise use of these strategies. With this rough application, participants will start to determine the units in bigger chunks, the size of which increases with augmenting time restrictions. In addition, the different arithmetical operations that are involved in the application of the addition and subtraction strategy will also be executed in a more sketchy fashion. This rough addition/subtraction strategy can also account for the observed effect of time pressure on the response times and accuracy of the items in the middle range. Indeed, the less time available, the bigger the chunks of blocks that participants will take into consideration and thus, the quicker but less accurate the addition or subtraction will be executed.

In sum, whereas the application of the addition/subtraction + estimation strategy starts with a relatively precise determination of the units followed by a global estimation of the remaining units after the stimulus has disappeared, the rough addition/subtraction strategy starts immediately with a relatively imprecise determination of the different (larger) subgroups of units in the stimulus material based on a sketchy execution of the arithmetical operations involved in the respective strategies. The observation of a significant negative correlation ($r(69) = -.48, p < .0001$) in the high time pressure condition between the response times and the deviation scores in the middle range of the numerosity continuum for participants who exhibited such a response-time pattern can be regarded as evidence for the application for the above-mentioned strategies.

Of course, participants may still have used other strategies instead of the addition/subtraction + estimation strategy or the rough addition/subtraction strategy to solve the trials in the middle range of the numerosity continuum. For instance, participants could have relied on some kind of benchmark estimation (Siegel, Goldsmith, & Madson, 1982) in which they used the judged numerosity for a particular item in the middle range as a benchmark to determine the numerosity of another item in that range. If it is perceived that the new item contains somewhat more blocks than the previous one, participants can add a certain amount of blocks to their benchmark to arrive at a final numerosity judgement. In the other case, they can subtract a certain amount of blocks from the same benchmark. Anyhow, the tracing of these strategies in the middle range of the numerosity continuum requires more fine-grained strategy-identification techniques, such as the recording of eye movements. The application of that research technique on the present task will be the focus of our next study.
As outlined in the introduction, Miller (1960) and Payne et al. (1988) summed up a number of changes in participants' performance that can occur as an effect of increasing time pressure. When we compare the effects of this extrinsic task variable on children's strategy use in the present study with the changes documented by these authors, we observe a number of similarities. As a first similarity we refer to the increase in processing speed of the different strategies with augmenting time pressure. Second, Miller and Payne et al. (1988) also mentioned an increased selectivity in information input as an effect of time pressure. The present study does not bear much direct evidence for this kind of adaptation but the possible rough application of the addition and subtraction strategy on the items in the middle range could be regarded as an expression of this type of adaptation. Indeed, increasing the size of the chunks of blocks or empty squares with augmenting time restrictions when executing these strategies can be considered as an increase in information selection. A last type of adaptation to time constraints that was pointed out by Miller and Payne et al. (1988) was a change in strategy preference. This type of adaptation was also observed in the present study: whereas the items in the middle range of the numerosity continuum in the low time pressure condition were mostly solved by means of the addition or subtraction strategy, participants in the moderate and severe time pressure condition tended to solve them with the estimation strategy, or with a number of alternative strategies such as the addition/subtraction + estimation strategy, or the rough variant of the addition and subtraction strategy.

Taken as a whole, these results demonstrate that time pressure affects children's strategy use in several ways. The fact that children are able to flexibly adapt their strategy use to the task environment can be interpreted as evidence for their extrinsic adaptiveness. As in previous studies (Luwel et al., 2003a, 2003b), this study has shown that the theoretical framework of Lemaire and Siegler (1995) cannot only be used to investigate developmental differences in strategy use but also to examine differences in strategy use among different conditions.

The present investigation was, due to its level of analysis, bound to be descriptive by demonstrating the different types of adaptation on the different dimensions of strategy use. However, future research should lead to a better understanding of the order in which the effects of time pressure occur. This type of studies could result in a theory that would allow us to predict which parameters of strategic competence would most likely be affected by constraining amounts of time pressure. Such theories would increase our knowledge of the mechanisms with which our cognitive system adapts to the demands of the situation, which in its turn can improve our understanding of the architecture of our cognitive system.
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