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MORAVEC

Cognitive arithmetic: extending the limits of data gathering

Introduction

Investigating **complex human cognitive faculties** such as arithmetic most often involves small groups of volunteers under a controlled environment.

Smartphone technology offers **high temporal and spatial resolution** with built-in millisecond timing of stimuli display and touchscreen responses, rendering a unique opportunity to perform massive cognitive longitudinal studies.

Exploiting these possibilities we designed M O R A V E C, an Android OS based app. This tool enables subjects to perform calculations anytime, anywhere, to collect **multiple variables** both on the subjects and on the app's use, including response times, usage patterns, perceived mental effort and confidence.

Two weeks after the app release, a total of **423 subjects** perform **120.000+ operations**. These numbers already are **orders of magnitude higher** than those reached in previous experiments in the area.

The main goal of this study was to invetigate if canonical experimental results in arithmetical cognition **can be replicated using smartphones,** despite the relatively uncontrolled environment.

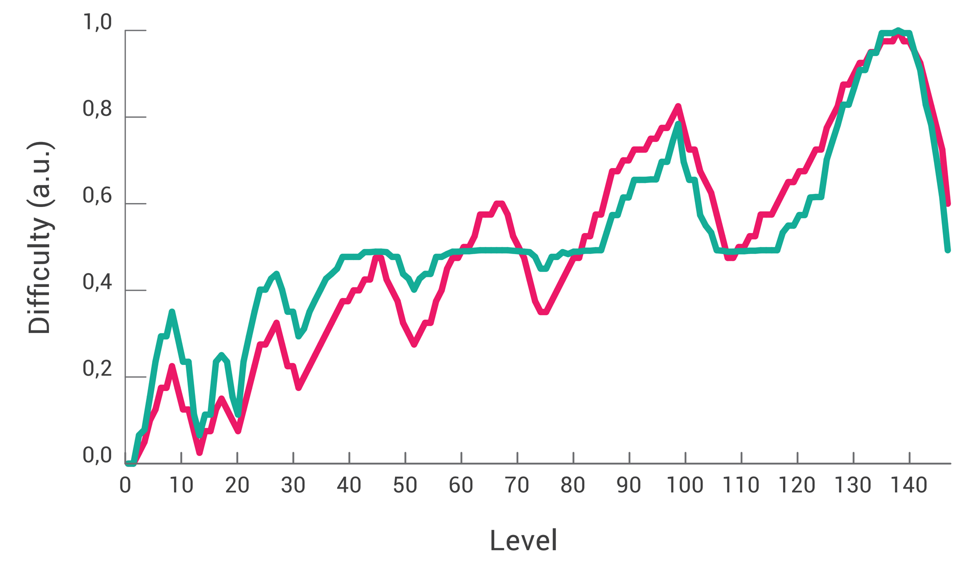
Methods

The main characteristics of Moravec's functionality are:

- Subjects are asked to perform different types of operations, from 1-digit additions to 4-digits squares.
- Levels are organized according to game design best-practices. In order to generate an engaging gameflow, difficulty is increased not linearly but as a series of increases and decreases.
- Data is gathered in real time employing smartphones connectivity and then analyzed offline.
- The app enables each user to monitor its own progress .
- In order to learn a practical method to mentally square numbers, a tutorial guide is provided.

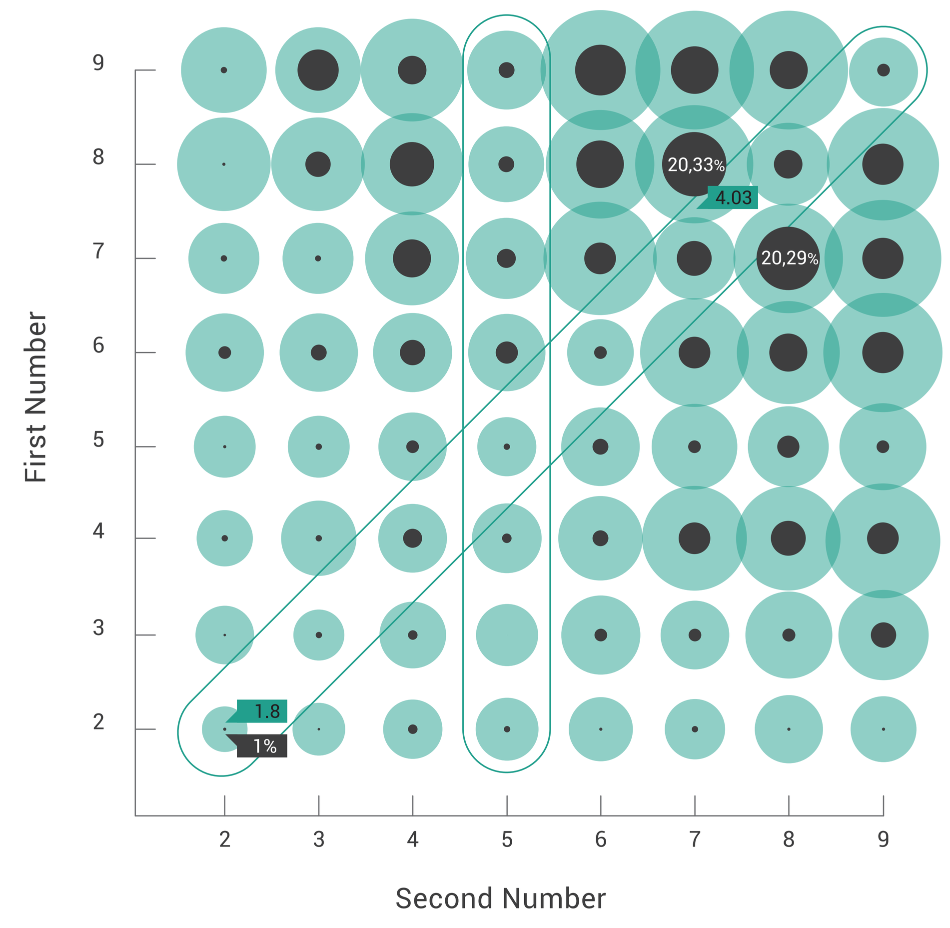
A **Facebook Group**, in which we updated news and encouraged users, was created. **Frequent posts regarding performance** were made, generating constant exchange between game **programmers/designers and users** as well as in between users.

fig. 1 Gameflow



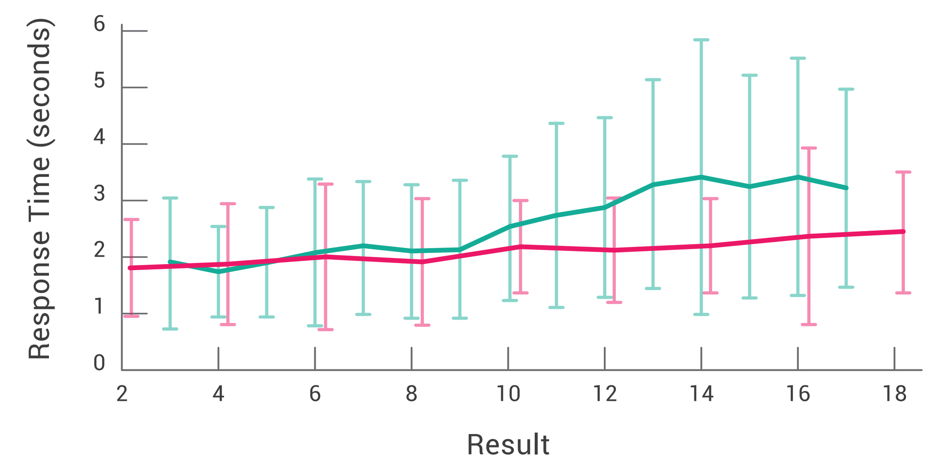
To generate an engaging experience, difficulty progresses as a series of increases and decreases. The difficulty in each level is shown according to a prediction theoreticized from the number of mental computations and memory load required by each operation (magenta). This correlates as expected with the measured Response Times (RTs) (green) after the experiment.

fig. 2 Performance



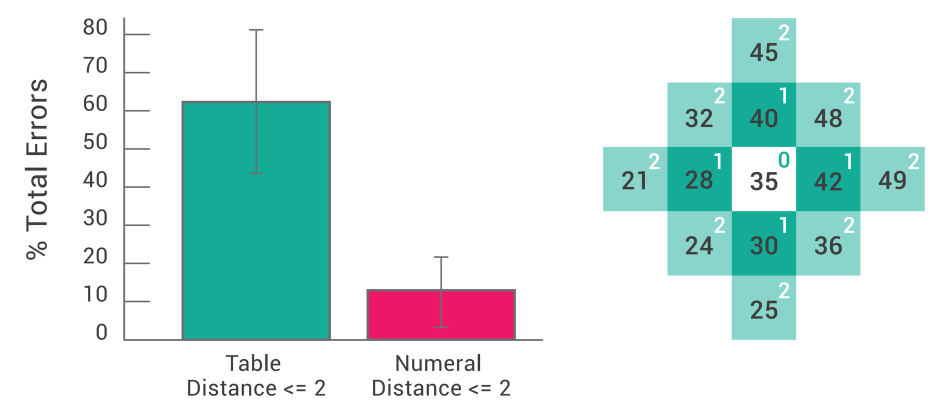
Average response times (green) and error rates (grey) for 1-digit multiplications. The diameter of the circles represent the magnitude of the measure. Larger numbers are more difficult - longer response times and larger error rates - with the exception of the equal-number multiplications and the table of 5.

fig. 3 Size Effect



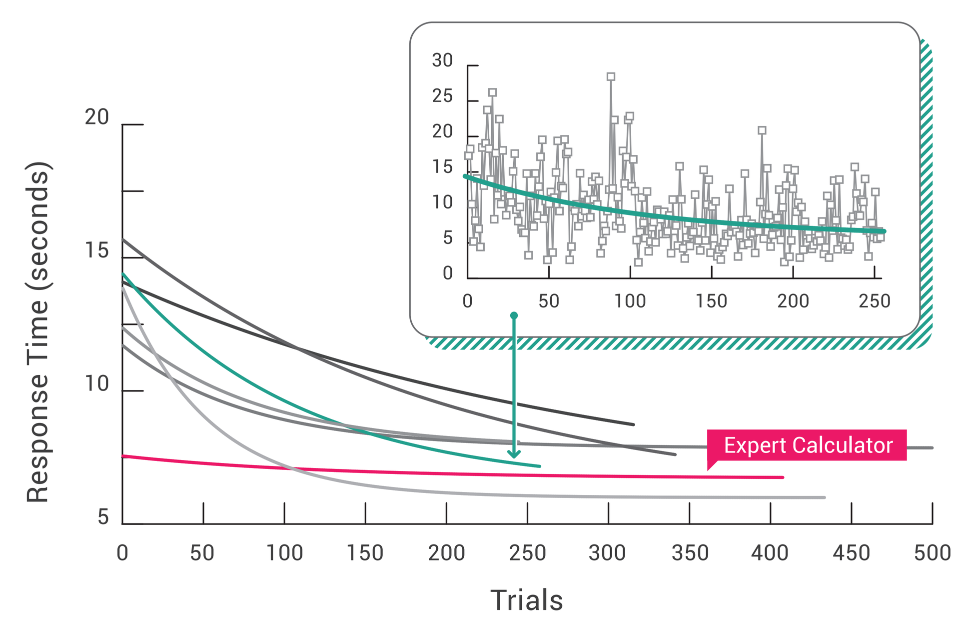
The time it takes for an adult to solve an addition problem increases with the size of the addends if the operands are different (green): slope = 0.12 seconds/number , intercept = 1.15 seconds (R^2=0.35, $F(1,17)$=149.22, p<0.001) but it is constant if the operands are equal (magenta): slope = 0.02 s/n, intercept = 1.62 s. (R^2=0.02, $F(1,17)$=3.67, p=0.06)

fig. 4 Frequent Errors



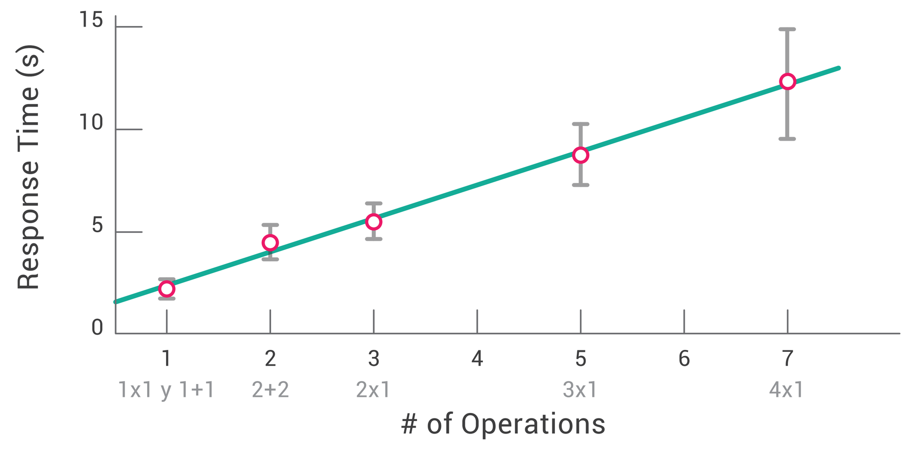
Most common mistakes correspond not to an absolute adjacent value (ie: to 5x7=35, respond 34=(5x7)-1) but to an adjacent table value (ie: to 5x7=35, respond 42=(5+1)x7). Considering 1 or 2 units distant from the correct answer, table errors (green) (M=0.63 SD=0.19 SE=0.04) are more frequent that numerical errors (magenta) (M=0.13 SD=0.09 SE=0.02), $t(52)$ = 12.21, p <0.001.

fig. 5 Learning Curves



Fitted exponential learning curves show how different subjects improve their response times (RTs) for 3dx1d operations. One subject even overperforms the expert calculator, who has been practicing for several years. In the insert, one of the fitted curves is plotted with the original data to show its accuracy.

fig. 6 SERIAL NATURE OF COMPLEX ARITHMETIC



Response times within a subject increase linearly with the number of steps each operation is decomposed in (ie: 726x4 requires 5 different operations: 3 products and 2 additions. 700x4 + 20x4 + 6x4). Slope = 1.63 seconds per operation. Intercept = 0.76 s. (R^2=0.86, $F(1,38)$=237.16, p<0.001)

CONCLUSIONS

From the data gathered, we were able confirm well-known results on mental arithmetic (Figures 2, 3 and 5) as well as to observe some new very interesting facts (Figures 4 and 6). Strong users were also able to learn how to square 3 and even 4 digit numbers in under one month of use, leading us to challenge the common definition of 'arithmetic prodigy'. Response time results suggest that complex arithmetic calculations are solved as a series of simple steps.
The fact that we could reproduce in two-weeks of data-gathering the main results that took years of laboratory work shows the potential of smartphones-based collaborative researches.