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Gerhard Marquart, Joost de Winter

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Workload Assessment for Mental Arithmetic Tasks using the Task-Evoked Pupillary Response

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Pupillometry is a promising method for assessing mental workload and could be helpful in the optimization of systems that involve human-computer interaction. The present study focuses on replicating the studies by Ahern (1978) and Klingner (2010), which found that for three levels of difficulty of mental multiplications, the more difficult multiplications yielded larger dilations of the pupil. Using a remote eye tracker, our research expands upon these two previous studies by statistically testing for each 1.5 s interval of the calculation period (1) the mean absolute pupil diameter (MPD), (2) the mean pupil diameter change (MPDC) with respect to the pupil diameter during the pre-stimulus accommodation period, and (3) the mean pupil diameter change rate (MPDCR). An additional novelty of our research is that we compared the pupil diameter measure with a self-report measure of workload, the NASA Task Load Index (NASA-TLX), and with the mean blink rate (MBR). The results showed that the findings of Ahern and Klingner were replicated, and that the MPD and MPDC discriminated just as well between the lowest and highest difficulty levels as did the NASA-TLX. The MBR, on the other hand, did not interpretably differentiate between the difficulty levels. Moderate to strong correlations were found between the MPDC and the proportion of incorrect responses, indicating that the MPDC was higher for participants with a poorer performance. For practical applications, validity could be improved by combining pupillometry with other physiological techniques.

Keywords: pupillometry, human factors, pupil diameter, cognitive load

Introduction

Mental workload is an important psychological construct that is challenging to assess on a continuous basis. A commonly used definition of mental workload is the one proposed by Hart and Staveland (1988). These authors defined workload as "the cost incurred by a human operator to achieve a particular level of performance." (p. 140). A valid and reliable assessment method of workload could be helpful in the optimization of systems that involve human-computer interaction, such as vehicles, computers, and simulators. One promising method for measuring workload is pupillometry, which is the measurement of the pupil diameter (e.g., Goldinger & Papesh, 2012; Granholm & Steinhauer, 2004; Klingner et al., 2008; Laeng et al., 2012; Marshall, 2007; Palinko et al., 2010; Schwalm et al., 2008).

Two antagonistic muscles regulate the pupil size, the sphincter and the dilator muscle. Activation of these muscles results in the contraction and dilation of the pupil, respectively. During a mentally demanding task, the pupils have been found to dilate up to 0.5 mm, which is small compared to the maximum dilation of about 6 mm caused by changes in lighting conditions (e.g., Beatty & Lucero-Wagoner, 2000). The involuntary reaction of the pupil to changes in task conditions is also called the task-evoked pupillary response (TEPR; Beatty, 1982). In the past, TEPRs were obtained at 1 to 2 Hz by motion picture photography (Hess & Polt, 1964). This required researchers to measure the pupil diameter manually frame by frame (Janisse, 1977). Nowadays, remote non-obtrusive eye trackers are increasingly being used to automatically measure TEPRs, as these devices are getting more and more accurate.

Over the years, researchers have encountered a few challenges in pupillometry. Reflexes of the pupil to changes in luminance, for example, may undermine the validity of TEPRs. One way to improve validity is to strictly control the luminance of the experimental stimuli, but this limits the usability of pupillometry. Marshall (2000) reported to have found a way to filter out the pupil light reflex using wavelet transform techniques. She patented this method and dubbed it the "index of cognitive activity". The influence of gaze direction on the measured pupil size is another issue. Whereas Pomplun and Sunkara (2003) reported a systematic dependence of pupil size on gaze direction,

56 Klingner et al. (2008) argued that the ellipse-fitting method for the estimation of the pupil size is not affected by
57 perspective distortion.
58
59 In the last few decades many researchers have investigated the pupillary response for different types of tasks.
60 Typically, the dilation was found to be higher for more challenging tasks (Ahern, 1978; Kahneman & Beatty, 1966),
61 including mental arithmetic tasks (Boersma et al., 1970; Bradshaw, 1968; Hess & Polt, 1964; Schaefer et al., 1968).
62 Not only task demands have been found to influence the pupil diameter, but also factors like anxiety, stress, and
63 fatigue. Tryon (1975) and Janisse (1977) extensively reviewed known sources of variation in pupil size. Back then,
64 Janisse (1977) commented on the underexplored area of whether pupillary dilations reliably reflect individual
65 differences in intelligence. Ahern (1978) discovered that persons scoring higher on intelligence tests showed smaller
66 pupillary dilations on tasks of fixed difficulty. In a more recent study, Van der Meer et al. (2010) found greater pupil
67 dilations for individuals with high intelligence than with low intelligence during the execution of geometric analogy
68 tasks. Thus, the results are not consistent and demand further investigation.
69
70 The present study focuses on replicating the pupil diameter study by Ahern (1978) for mental multiplications of
71 varying levels of difficulty. Ahern (1978) found that the more difficult multiplications yielded a greater mean pupil
72 diameter. In her research, Ahern (1978) used a so-called television pupillometer (Whittaker 1050S) that was able to
73 measure the pupil diameter in real-time. Specifically, the device processed images obtained from an infrared video
74 camera, identified the pupil diameter using a pattern-recognition algorithm, and computed the diameter of the image
75 of the pupil (Beatty & Wilson, 1977). Participants used a chin-rest and infrared eye illuminator, and the camera was
76 positioned approximately 15 cm from the participant's left eye. Our study is also intended as a follow-up study of
77 Klingner (2010). Klingner (2010) recently replicated Ahern's (1978) results with a remote eye tracker (Tobii 1750)
78 having a similar working principle as the eye-tracked used by Ahern (1978). In Klingner (2010), the participants sat
79 approximately 60 cm from the screen and infrared cameras, and they did not use a chin-rest or head-mounted
80 equipment. In his analyses, Klingner (2010) used the average of the two eyes' pupil diameters. With more
81 participants (30 in our study, 24 in Ahern, 1978, 12 in Klingner, 2010), more trials (1350, 768, and 632,
82 respectively), and a higher measurement frequency (120 Hz, 20 Hz, and 50 Hz, respectively), the present study
83 aimed to obtain the TEPRs for three levels of difficulty of mental multiplications.
84
85 We report the mean pupil diameter change (MPDC) with respect to the baseline pupil diameter right before the
86 presentation of the multiplicand, as was also done by Ahern (1978) and Klingner (2010). In addition, we report the
87 absolute mean pupil diameter (MPD). Laeng et al. (2012) explained that pupil diameter responses exhibit both a
88 phasic component (i.e., 'rapid' responses to task-relevant events) as well as a tonic component (i.e., 'slow' changes
89 in the baseline pupil diameter). The MPDC allowed us to assess the TEPR, while the MPD allowed us to determine
90 whether the baseline itself differed as a function of the difficulty of the multiplications. Furthermore, in our study,
91 the mean pupil diameter change rate (MPDCR), a measure introduced by Palinko et al. (2010), was examined. The
92 MPDCR is the discrete-time equivalent to the first derivative of the pupil diameter and may be useful for assessing
93 moment-to-moment changes in mental workload. While Ahern (1978) and Klingner (2010) statistically compared
94 the maximum dilation and mean dilation among the difficulty levels of the mental multiplications, we applied a
95 more fine-grained approach where the MPDC, MPC, and MPDCR were subjected to a statistical test for each 1.5 s
96 time interval in the calculation period. Another way in which our research differs from the works of Ahern (1978)
97 and Klingner (2010) is that we included two additional measures of mental workload. First, we compared the effect
98 sizes of the pupil diameter measures with those obtained with a classic subjective measurement method of workload,
99 the NASA-TLX. Second, we assessed the mean blink rate (MBR). The relation between mental workload and blink
100 rate has been unclear (Kramer, 1990; Recarte et al., 2008; Marquart et al., 2015), and our aim was to clarify this
101 relationship.
102
103 The numbers in our study were presented visually in order to gain temporal consistency, as was also done by
104 Klingner (2010; cf. Ahern, 1978, in which the numbers were presented aurally). Furthermore, as in Klingner (2010),
105 the pupil diameter was recorded with an automatic remote eye tracker (SmartEye DR120).
106
107 **Method**
108
109 **Ethics Statement**

110   The research was approved by the Human Research Ethics Committee (HREC) of the Delft University of
111   Technology (TU Delft 'Workload Assessment for Mental Arithmetic Tasks using the Task-Evoked Pupillary
112   Response', date: January 29, 2015). All participants provided written informed consent.
113
114   **Participants**
115   Thirty participants (2 women and 28 men), aged between 19 and 38 years ($M = 23$, $SD = 4.1$ years) were recruited to
116   volunteer in this experiment (25 BSc/MSc students and 5 persons with an MSc degree). Individuals wearing glasses
117   or lenses were excluded from participation. All participants read and signed an informed consent form, explaining
118   the purpose and procedures of the experiment and received €5 compensation for their time.
119
120   **Equipment**
121   The SmartEye DR120 remote eye tracker, with a sampling rate of 120 Hz, was used to record the participant's pupil
122   diameter, eyelid opening, and gaze direction while sitting behind a desktop computer (see Fig. 1). The pupil
123   diameter was the average of the left and right pupil diameter, as provided by the SmartEye 6.0 software. In order to
124   obtain more accurate measurements, a chin-rest was used. The eye tracker was equipped with a 24-inch screen,
125   which was positioned approximately 65 cm in front of the sitting participant and which was used to display task-
126   relevant information. The outcome of a task had to be entered using the numeric keypad of a keyboard (cf. Ahern,
127   1978 in which participants used a keyboard, and Klingner, 2010 in which participants used a touchscreen).
128
129   The experiment took place in a room where there was office lighting delivered by standard fluorescent lamps and
130   where daylight could not enter. Our approach to room illumination was similar to that used by Klingner (2010). We
131   acknowledge that a stricter control of lighting is possible. For example, Janisse (1977) reported that he ensured
132   constant illumination of his experimental lab by feeding all electric current used in the room through a constant
133   voltage transformer. No such strict control of illumination was applied in our research nor did we measure the
134   degree of ambient lighting. However, because the experimental conditions were counterbalanced, we reasoned that
135   there could be no systematic effect of ambient lighting on our results. Furthermore, we used a screen background
136   with variable brightness, designed to minimize the pupillary light reflex in case a participant looked away from the
137   center of the screen (Fig. 2; Marquart, 2015). The corresponding image file is available in the supplementary
138   materials.
139
140   **Procedure**
141   The participants were requested to perform 50 trials of mental arithmetic tasks (multiplications of two numbers),
142   five of which were used as a short training. The remaining 45 trials were presented in three sessions of different
143   levels of difficulty (easy, medium, and hard; see Table S1). Level 1 contained the 15 easiest multiplications
144   (outcomes ranging between 80 and 108), Level 2 contained 15 multiplications of intermediate difficulty (outcomes
145   between 126 and 192), and Level 3 contained the 15 hardest multiplications (outcomes between 221 and 324).
146
147   The sequence of the three sessions was counterbalanced across the participants. Each trial was initiated by the
148   participant by pressing the enter key and started with a 4 s accommodation period, followed by a 1 s visual
149   presentation of two numbers (multiplicand and multiplier) between 6 and 18, with a 1.5 s pause in between (Table
150   1). The participants were asked to multiply the two numbers and type their answer on the numeric keypad 10 s after
151   the multiplier disappeared. Thus, the total duration of one trial was 17.5 s (4 + 1 + 1.5 + 1 + 10). When the numbers
152   were not presented, a double "X" was shown to avoid pupillary reflexes caused by changes in brightness or contrast.
153
154   After each of the three sessions, participants were asked to fill out a NASA-TLX questionnaire to assess their
155   subjective workload on six facets: mental demand, physical demand, temporal demand, performance, effort, and
156   frustration (Hart & Staveland, 1988). All questions were answered on a scale from 0 % (very low) to 100 % (very
157   high). For the performance question, 0 % meant perfect and 100 % was failure. The participants' overall subjective
158   workload was obtained by averaging the scores across the six items. The total duration of the experiment was
159   approximately 30 minutes.
160
161   **Instructions to Participants**
162   Before the experiment started, the participants were informed that they had to do 50 multiplications, five of which
163   would be used as a short training. They were also told that the remaining 45 trials were presented in three sessions of
164   varying difficulty (easy, medium, and hard). The participants were requested to position themselves in front of the
165   monitor with their chin leaning on the chin-rest. They were instructed to stay still and keep their gaze fixed and

166 focus (not stare) at the center of the screen throughout a trial. In addition, participants were asked to blink as little as
167 possible, obviously without causing irritation, and to start each trial with 'a clear mind' (i.e., not thinking about the
168 previous trial). If the participants could not complete the multiplication, they were instructed to enter zero as their
169 answer.
170
171 **Data Processing**
172 The data were processed in two steps. In the first step, the missing values in the pupil diameter data (lost during
173 recording) were removed and the signals were repaired with linear interpolation (see Fig. 3A, for an illustration). On
174 average, 1.2% of the data were lost, so this processing step did not substantially influence the results. In the second
175 step, blinks and poor-quality data were removed. During a blink, the eyelid opening rapidly diminishes and then
176 increases in a few tenths of a second until it is fully open again. It is impossible to track the pupil diameter while
177 blinking. The pupil diameter quality signal (provided by the SmartEye software) was used to filter out the poor
178 quality data. This signal ranges from 0 to 1, with values close to 1 indicating a good quality (SmartEye AB, 2013).
179 All data points with a pupil diameter quality below 0.75 were removed. Trials containing less than 70% of the data
180 were excluded from the analysis. Of the initial 1350 trials from 30 participants, 1125 trials passed these criteria (394
181 for Level 1, 384 for Level 2, & 347 for Level 3; the entire level 2 session of one participant [15 trials] was
182 discarded). The gaps in the 1125 trials were filled using linear interpolation (Fig. 3B).
183
184 The last 0.4 s of the accommodation period were defined as the pupillary baseline, as was done by Klingner (2010).
185 The mean pupil diameter of the baseline period (3.6–4.0 s) of each trial was subtracted from each trial to
186 accommodate for any possible shifts or drifts. The mean pupil diameter change (MPDC) for each participant was
187 then obtained by averaging all trials per level of difficulty. Similarly, the mean pupil diameter (MPD) for each
188 participant was obtained but then without subtracting the mean pupil diameter of the baseline period. The MPDCR
189 was calculated for each participant as the average velocity (mm/s) or change in MPD between two points in time. In
190 order to compare the three difficulty levels, the MPD and MPDC were analyzed at eight fixed points in time from
191 the multiplier and calculation periods (i.e., P1 = 6.5 s, P2 = 7.5 s, P3 = 9.0 s, P4 = 10.5 s, P5 = 12.0 s, P6 = 13.5 s,
192 P7 = 15.0 s, P8 = 16.5 s). The MPDCR was assessed across the seven interim periods.
193
194 In addition to these analyses, the mean blink rate (MBR) for two different periods in time was calculated. That is, a
195 distinction was made between low mental demands (i.e., from the beginning of the accommodation period until the
196 presentation of the multiplier; i.e., from 0 to 6.5 s) and high mental demands (i.e., from the presentation of the
197 multiplier until the end of the calculation period; i.e., from 6.5 to 17.5 s). A blink was defined as the moment that the
198 eye opening dropped below 75% of the mean eyelid opening of that trial (see Fig. S1).
199
200 **Statistical Analyses**
201 The pupil diameter measures (MPD, MPDC, and MPDCR), the blink rates (MBR), and the results of the NASA-
202 TLX were analyzed with paired *t*-tests between the three levels (i.e., Level 2 vs. 1, Level 3 vs. 1, and Level 3 vs. 2).
203 Additionally, Pearson's *r* correlation coefficients were obtained between the MPDC and the NASA-TLX and
204 responses. For all analyses, a Bonferroni correction was applied. Accordingly, we set the significance level to 0.05/3
205 (~ 0.0167).
206
207 Cohen's d_z effect size (see Eq. 1) was calculated to determine at which points in time the differences in MPDC
208 between the three levels of difficulty were largest. In Equation 1, *M* and *SD* are the mean and standard deviation of
209 the vector of data points, respectively, *r* is the Pearson correlation coefficient between the two vectors of data points,
210 *t* is the *t*-statistic of a paired *t*-test, and *N* is the sample size (i.e., the number of pairs, which was either 29 or 30).
211

212 $$d_z = \frac{M_i - M_j}{\sqrt{SD_i^2 + SD_j^2 - 2*r*SD_i*SD_j}} = \frac{t}{\sqrt{N}} \quad (1)$$

213
214 **Results**
215
216 **Mean Pupil Diameter (MPD)**
217 The MPD during the mental multiplication task is shown in Figure 4. It can be seen that at all points in time, the
218 MPD was higher for the higher levels of difficulty. The pattern of the MPD was similar for all levels during the first

219 ten seconds. Figure also shows the results for the period 6.5–17.5 s, split into seven periods with eight points. The
220 means and standard deviations of the MPD for the eight points in time and the three levels of difficulty are shown in
221 Table 2, together with the effect sizes (d_z) and the p-values of the pairwise comparisons. The results confirm that the
222 MPD was significantly higher for the more difficult levels at all points in time.
223
224 **Mean Pupil Diameter Change (MPDC)**
225 Figures 5 shows the MPDC as a function of the level of difficulty. As mentioned above, this measure takes into
226 account the shift of the baseline by subtracting the mean of the baseline period of each trial. The difference between
227 the three pupillary responses during the calculation period can now be seen more clearly as compared to the MPD.
228 Again, the multiplier and calculation were split into seven periods by eight points. The results of the analysis of the
229 MPDC at the eight points in time and three levels of difficulty are shown in Table 2. A significant difference
230 occurred at Points 4 to 8. The effect size estimate Cohen's d_z was also calculated for the MPDC between pairs of
231 difficulty levels for each point in time (see Fig. 6). It can be seen that large effect sizes arose after approximately 11
232 s since the start of the trial, especially between Levels 1 and 3.
233
234 **Mean Pupil Diameter Change Rate (MPDCR)**
235 Figure 7 shows the MPDCR as a function of the difficulty level, for the seven periods. A positive value indicates
236 overall pupil dilation during that period and a negative value means overall contraction of the pupil diameter. In the
237 first two periods, the diameter increased with approximately equal velocity for the three levels. During the other
238 periods, the velocities decreased and became negative. Significant differences were found between the three
239 conditions (see also Table 2).
240
241 **Self-Reported Workload (NASA-TLX)**
242 The results of the NASA-TLX questionnaire are shown in Figure 8. For almost all items, the TLX score was
243 significantly higher for the more difficult multiplications (see also Table 2). Only the subjective physical workload
244 did not differ significantly between the levels of difficulty.
245
246 **Pupil Diameter of Correct Versus Incorrect Responses**
247 The percentages of correct responses for Levels 1, 2, and 3 were respectively 94.7%, 92.9%, and 66.4% when
248 selecting all 450 trials per level. When considering only those trials which passed the data filtering (see section Data
249 Processing), the percentages of correct responses for Levels 1, 2, and 3 were respectively 94.2% (371 of 394 trials),
250 93.8% (360 of 384 trials), and 69.2% (240 of 347 trials). Figure 9 shows the MPD for Level 3 separated into correct
251 and incorrect responses. Too few incorrect answers were given for the other two levels and the results for these
252 levels are therefore not reported. There were no significant differences between the MPD for correct and incorrect
253 responses (Table S2).
254
255 **Blink Rate**
256 Table 2 shows that the MBR of Level 3 was higher, but not significantly so, than the MBR of Levels 1 and 2.
257 However, for each level of difficulty, the MBR was higher during periods with low mental demands (0–6.5 s) than
258 during higher mental demands (6.5–17.5 s). Figure 10 illustrates the cumulative number of blinks as a function of
259 time. It can be seen that participants were likely to blink at distinct moments in time, namely right after the start of
260 the trial (~ 0.5 s), right after the presentation of the multiplicand (~ 4.5 s), and after the presentation of the multiplier
261 (~ 8.0 s).
262
263 **Correlations between MPDC, NASA-TLX, and proportion of incorrect responses**
264 The results of the correlation analyses between the MPDC, NASA-TLX, and proportion of incorrect responses are
265 shown in Table 3. For the MPDC, the table shows overall positive correlations, for the eight points in time and for
266 the three different levels of difficulty. Between the MPDC and the percentage of incorrect responses, three
267 statistically significant positive correlation coefficients were observed at Points 1 and 2. Furthermore, Table 3 shows
268 that people who experienced higher subjective workload (i.e., a higher NASA-TLX score) generally gave more
269 incorrect responses.
270
271 **Discussion**
272
273 **Pupil Diameter Results**

274 The results showed that the MPD was higher for the higher levels of difficulty at all eight points of the calculation
275 period, with Points 7 and 8 exhibiting the largest differences. The MPD findings demonstrate that the baseline of the
276 pupil diameter can shift during mental activity. If the pupil was given more time to recover from the previous trial,
277 by increasing the length of the accommodation period, the difference of the MPD between the three levels of
278 difficulty in the first period would probably have been smaller.
279
280 A remarkable finding is the behavior of the MPD during the first 2.5 s of the accommodation period. Where a clear
281 decline from the start or a horizontal line might be expected, the MPD starts to decline only after about 2.5 s. This
282 unexpected finding may have been caused by the fact that participants looked away from the center of the screen
283 when their outcome to the multiplication had to be entered. Although the responses were not given during the
284 accommodation period, the fluctuation could be an aftereffect because the trials came in relatively quick succession.
285 During the presentation of the multiplicand and the pause (4–6.5 s) the MPD decreased further, at a slower pace
286 however, which seems to indicate memory load (cf. Kahneman & Beatty, 1966). A small increase of the pupil
287 diameter after the presentation of the first number was observed by Ahern (1978) and Klingner (2010).
288
289 The MPDC has the advantage compared to MPD that it corrects for fluctuations in the baseline pupil diameter, and
290 hence compensates for any structural temporal trends that might exist. The use of MPDC is appropriate as compared
291 to other types of measures such as percent dilation, because as pointed out by Beatty and Lucero-Wagoner (2000),
292 "the pupillary dilation evoked by cognitive processing is independent of baseline pupillary diameter over a wide
293 range of baseline values." (p. 148). What is notable in the MPDC results (Fig. 5) is that the pupillary behavior
294 among the three difficulty levels was highly similar during the first few seconds after the presentation of the
295 multiplier (6.5–9 s). This might be due to the strategy that the participants used. One can imagine that the first step
296 in each multiplication, regardless of its difficulty, is similar. For example, the first step for many people of the Level
297 1 multiplication 7x14 would probably be 7x10. This is comparable to the first step of the Level 3 multiplication
298 14x18, which would then be 14x10. These observations are in line with the TEPRs obtained by Ahern (1978), who
299 observed a similar response among the three levels of difficulty at the beginning of the calculation. The MPDC
300 during the other periods was found to differ significantly between the three levels, particularly when Levels 1 and 2
301 were compared to Level 3.
302
303 The results of the MPDCR illustrate that the effect sizes are smaller when compared to the results of the MPDC
304 measure. Presumably, the MPDCR is less sensitive to changes in mental workload because it represents second-to-
305 second changes in pupil diameter rather than the actual pupil diameter itself (either absolutely as in the MPD, or
306 relative to a baseline as in the MPDC). As with any first-order derivative of a signal, the MPDCR might be more
307 sensitive to noise and unsystematic moment-to-moment fluctuations in pupil diameter. Nonetheless, the MPDCR
308 does provide a clear indication of when the muscles of the pupil respond, and hence when the mental workload
309 increases or decreases.
310
311 An interesting question related to Figure 9 showing the trials with the correct versus incorrect responses is: Were the
312 participants really trying to complete the task or did they give up on the task because it was too difficult? If the latter
313 were the case, one would expect an early decline of the MPD. But the opposite is true, instead. A small increase of
314 the MPD was measured, suggesting that the participants were trying hard to complete the task until the time was up.
315
316 **Self-Reported Workload (NASA-TLX)**
317 According to the results of the NASA-TLX questionnaire, the classification of the arithmetic tasks was done
318 properly, since a statistically significant difference was found in the subjective mental workload across all three
319 levels. The large contrast between the subjective mental and physical workload underlines that the task was
320 predominantly mentally rather than physically demanding. Not to be overlooked are the roles of the subjective
321 temporal demand and frustration. Looking at the increase of the MPD of the incorrect responses after 12 s for Level
322 3 (Fig. 9), it is plausible that, although the results were not statistically significant, this increase was caused by the
323 time pressure of the task or the anxiety or frustration of not having solved the multiplication yet, instead of increased
324 task demands.
325
326 **Blink Rate**
327 The relation between mental workload and blink rate has been unclear in the literature (e.g., Kramer, 1990; Recarte
328 et al., 2008; Marquart et al., 2015). The results in the present study show that the MBR was slightly higher for Level
329 3 than for Levels 1 and 2. Contrastingly, the MBR was higher during the low mental demand period (0–6.5 s) than

330 during the high demand period (6.5–17.5). The temporal analysis (Fig. 10) indicated that people blinked particularly
331 at those moments when the visual demand was reduced, such as right after the start of the task, and right after the
332 presentation of the multiplier. In summary, consistent with prior research, the relationship between mental workload
333 and blink rate is complex, and it appears that blink rate is governed not only by mental demands, but also by visual
334 demands (see also Marquart et al., 2015).
335
336 **Correlations between MPDC, NASA-TLX, and proportion of incorrect responses**
337 Moderate to strong correlations were found between the MPDC and the proportion of incorrect responses. A similar
338 but weaker effect was obtained between the MPDC and the NASA-TLX. Thus, the MPDC was higher for
339 participants who gave more incorrect responses and who reported a higher workload in the NASA-TLX. Negative
340 correlations between the pupil diameter and the proportion of correct responses and NASA-TLX were also found by
341 Ahern (1978), Payne et al. (1968), and Recarte et al. (2008). These findings could be useful for determining the
342 feasibility of using the pupil diameter in human-machine applications such as adaptive automation, which is "an
343 approach to automation design where tasks are dynamically allocated between the human operator and computer
344 systems" (Byrne & Parasuraman, 1996, p. 249).
345
346 **Conclusions and Recommendations**
347 It is concluded that the results of Ahern (1978) and Klingner (2010) have been accurately replicated with the
348 SmartEye DR120 remote eye tracker. The Cohen d_z effect sizes between the MPDC of Level 1 and Level 3 was 1.98
349 at maximum (at Point 8), which was about the same ($d_z = 1.94$) as the NASA-TLX overall score. This finding
350 demonstrates that pupil diameter measurements can be just as valid as the NASA-TLX. In our research, an attempt
351 was made to provide more insight into the individual differences of TEPRs by means of a correlation analysis.
352 Results showed a few moderate to strong correlations at the beginning of the calculation period between the MPDC
353 and the NASA-TLX, on the one hand, and the ratio of incorrect responses, on the other.
354
355 Thus, it seems possible to assess workload by tracking the pupil diameter. However, the validity of pupil diameter
356 measurements may need improvement before it could be implemented in practice. Future research could focus on
357 improving signal analysis techniques that filter out effects other than mental workload, such as the light reflex. It is
358 challenging to enhance the applicability of pupillometry towards tasks that require fixation on different types of
359 targets. Janisse (1977) previously concluded that research that uses pictorial stimuli should "be interpreted with
360 caution, and perhaps be discounted." (p. 77). One possible way to use the pupil diameter in visually complex tasks
361 might be to correct in real time for the amount of light that enters the eye. Janisse proposed such approach as early
362 as 1977: "The simultaneous monitoring of pupil size and eye movements (points of focus) as subjects view pictorial
363 stimuli might allow one to mathematically 'correct' pupil size as a function of the brightness of the on which the
364 subject's gaze is falling at a given time." (p. 189). Because modern remote eye trackers measure gaze direction and
365 pupil diameter simultaneously, such approach becomes within practical reach, as also discussed by Klingner (2010).
366 For further reading into approaches of pupillometry in complex visual environments, see Palinko and Kun (2011; a
367 driving simulator), and Klingner (2010; visual search and map reading).
368
369 Additionally, validity could be improved by combining pupillometry with other physiological measures (e.g.,
370 Haapalainen et al., 2010; Just et al., 2003; Kahneman et al., 1969; Molen et al., 1989; Satterthwaite et al., 2007). For
371 example, Haapalainen et al. (2010) used an electrocardiogram (ECG)-enabled armband, a remote eye tracker, and a
372 wireless electroencephalogram (EEG) headset to collect various physiological signals simultaneously. The authors
373 concluded that the heat flux and heart rate variability in combination provided a classification accuracy of over 80%
374 between conditions of low and high mental workload. In this study, the pupil diameter did not perform strongly as a
375 classifier (57%) presumably due to data loss of the eye tracker. A primary advantage of pupillometry in such
376 multivariate applications is that the pupil diameter reacts rapidly to changes in task conditions (cf. Fig. 5), while
377 measures such as heat flux, galvanic skin response, or heart rate have considerably longer time constants.
378
379 The supplementary materials provide the measurement data, software, and scripts that would allow others to
380 reproduce these results: https://www.dropbox.com/s/s8iap0re1kfw13c/Supplementary_material_July_2015.zip?dl=0
381
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459

Table 1. Timeline of an individual trial.

Period	Start time (s)	End time (s)	Symbol
Accommodation	0.0	4.0	XX
Baseline	3.6	4.0	XX
Multiplicand	4.0	5.0	08
Pause	5.0	6.5	XX
Multiplier	6.5	7.5	16
Calculation	7.5	17.5	XX
Response	17.5	when pressing enter key	N/A

Mean pupil diameter (MPD), mean pupil diameter change (MPDC), mean pupil diameter change rate (MPDCR), NASA-TLX, and mean blink rate (MBR), per level of difficulty of the multiplications.

The means (*M*) and standard deviations (*SD*) are shown per level of difficulty of the multiplications. P1–P8 refers to the eight points in time, while (1)–(7) refers to the seven periods. Statistically significant differences are indicated in boldface. *N* = 30 for the NASA-TLX for all three levels.

	M (SD)			*p*-value (d_z)		
	Level 1 **(N = 30)**	**Level 2** **(N = 29)**	**Level 3** **(N = 30)**	**Level 2 vs. 1** **(df = 28)**	**Level 3 vs. 1** **(df = 29)**	**Level 3 vs. 2** **(df = 28)**
MPD (mm)						
P1	3.748 (0.456)	3.804 (0.467)	3.873 (0.490)	0.334 (0.19)	**0.001** (0.73)	0.026 (0.44)
P2	3.796 (0.480)	3.865 (0.486)	3.949 (0.516)	0.119 (0.30)	**< 0.001** (0.86)	**0.009 (0.53)**
P3	3.904 (0.470)	3.979 (0.481)	4.051 (0.531)	0.107 (0.31)	**< 0.001** (0.81)	0.036 (0.42)
P4	3.891 (0.456)	4.003 (0.478)	4.113 (0.522)	0.037 (0.41)	**< 0.001** (1.06)	**0.007 (0.55)**
P5	3.827 (0.429)	3.948 (0.488)	4.136 (0.521)	0.017 (0.48)	**< 0.001** (1.50)	**< 0.001 (0.86)**
P6	3.752 (0.451)	3.894 (0.490)	4.122 (0.518)	0.017 (0.48)	**< 0.001** (1.60)	**< 0.001 (0.89)**
P7	3.709 (0.427)	3.815 (0.474)	4.130 (0.500)	0.051 (0.39)	**< 0.001** (1.76)	**< 0.001 (1.28)**
P8	3.676 (0.436)	3.781 (0.460)	4.108 (0.493)	0.064 (0.36)	**< 0.001** (1.97)	**< 0.001 (1.23)**
MPDC (mm)						
P1	-0.118 (0.087)	-0.114 (0.115)	-0.093 (0.085)	0.837 (0.04)	0.158 (0.27)	0.424 (0.15)
P2	-0.069 (0.094)	-0.052 (0.118)	-0.017 (0.120)	0.310 (0.20)	**0.016** (0.48)	0.218 (0.24)
P3	0.038 (0.148)	0.061 (0.148)	0.084 (0.152)	0.297 (0.20)	0.107 (0.31)	0.452 (0.14)
P4	0.026 (0.179)	0.086 (0.149)	0.147 (0.171)	0.039 (0.41)	**0.001** (0.66)	0.093 (0.33)
P5	-0.038 (0.204)	0.031 (0.164)	0.169 (0.205)	**0.013** (0.50)	**< 0.001** (1.15)	**< 0.001** (0.75)
P6	-0.113 (0.196)	-0.024 (0.193)	0.155 (0.228)	**0.012** (0.51)	**< 0.001** (1.53)	**< 0.001** (0.87)
P7	-0.156 (0.186)	-0.102 (0.207)	0.164 (0.226)	0.044 (0.40)	**< 0.001** (1.97)	**< 0.001** (1.37)
P8	-0.190 (0.179)	-0.136 (0.208)	0.143 (0.248)	0.115 (0.31)	**< 0.001** (1.98)	**< 0.001** (1.22)
MPDCR (mm/s)						
(1)	0.048 (0.087)	0.062 (0.079)	0.076 (0.112)	0.210 (0.24)	0.068 (0.35)	0.463 (0.14)
(2)	0.072 (0.080)	0.076 (0.069)	0.067 (0.081)	0.696 (0.07)	0.765 (-0.06)	0.698 (-0.07)
(3)	-0.008 (0.078)	0.016 (0.070)	0.042 (0.055)	0.094 (0.33)	**0.002** (0.62)	0.088 (0.33)
(4)	-0.043 (0.052)	-0.037 (0.057)	0.015 (0.052)	0.606 (0.10)	**< 0.001** (1.01)	**< 0.001** (0.75)
(5)	-0.050 (0.060)	-0.036 (0.059)	-0.009 (0.067)	0.514 (0.12)	0.021 (0.45)	0.052 (0.38)
(6)	-0.029 (0.051)	-0.053 (0.053)	0.006 (0.060)	0.098 (-0.32)	**0.015** (0.48)	**< 0.001** (0.80)
(7)	-0.022 (0.052)	-0.022 (0.062)	-0.014 (0.051)	0.827 (-0.04)	0.514 (0.12)	0.372 (0.17)
NASA-TLX (%)						
Total	21 (13)	31 (13)	49 (14)	**< 0.001** (0.88)	**< 0.001** (1.94)	**< 0.001** (1.51)
Mental	34 (21)	47 (17)	70 (17)	**0.002** (0.64)	**< 0.001** (1.41)	**< 0.001** (1.53)
Physical	16 (17)	19 (19)	20 (20)	0.045 (0.39)	0.118 (0.30)	0.707 (0.07)
Temporal	19 (15)	29 (18)	53 (23)	**0.004** (0.57)	**< 0.001** (1.43)	**< 0.001** (1.28)
Performance	10 (12)	21 (17)	40 (23)	**0.002** (0.63)	**< 0.001** (1.48)	**< 0.001** (0.93)
Effort	28 (19)	43 (17)	64 (22)	**< 0.001** (0.77)	**< 0.001** (1.37)	**< 0.001** (1.17)
Frustration	18 (17)	27 (24)	45 (29)	**0.005** (0.57)	**< 0.001** (1.23)	**< 0.001** (0.86)
MBR (blinks/s)						
(0.0–6.5 s)	0.262 (0.165)	0.258 (0.168)	0.303 (0.216)	0.748 (0.06)	0.203 (0.24)	0.265 (0.21)
(6.5–17.5 s)	0.218 (0.187)	0.212 (0.175)	0.265 (0.210)	0.861 (0.03)	0.078 (0.34)	0.023 (0.45)

Pearson's correlations (*r*) between the mean pupil diameter change (MPDC), percentage of incorrect responses, and the overall NASA-TLX scores, for the three levels of difficulty.

Statistically significant correlations are indicated in boldface.

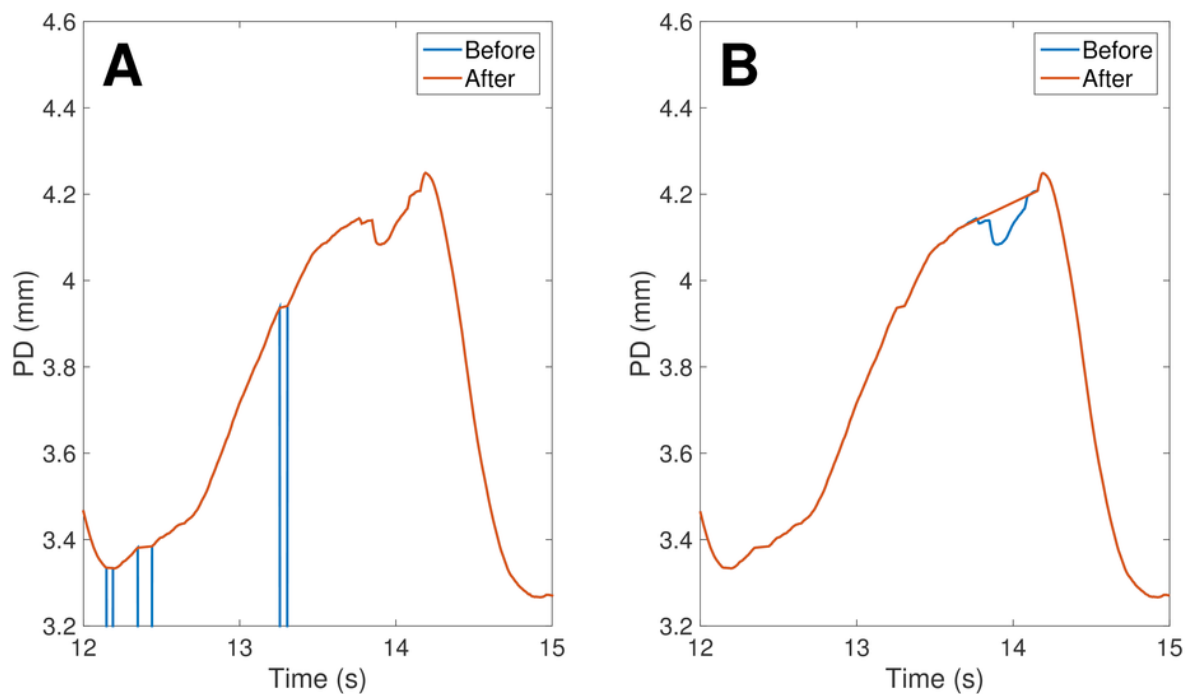
	Level 1	Level 2	Level 3	Mean of Levels 1–3
	r (p-value)	r (p-value)	r (p-value)	r (p-value)
MPDC vs. Overall NASA-TLX				
P1	-0.02 (0.899)	0.20 (0.310)	0.20 (0.283)	0.33 (0.072)
P2	-0.22 (0.239)	0.29 (0.130)	0.09 (0.644)	0.17 (0.376)
P3	-0.15 (0.523)	0.04 (0.818)	0.01 (0.978)	0.01 (0.965)
P4	0.09 (0.435)	0.07 (0.733)	0.04 (0.833)	0.17 (0.365)
P5	0.11 (0.641)	0.11 (0.554)	0.02 (0.925)	0.09 (0.654)
P6	0.05 (0.550)	0.20 (0.307)	-0.01 (0.952)	0.09 (0.637)
P7	0.05 (0.813)	0.20 (0.290)	0.17 (0.363)	0.14 (0.469)
P8	-0.00 (0.998)	0.26 (0.176)	0.16 (0.385)	0.18 (0.349)
MPDC vs. % Incorrect responses				
P1	0.34 (0.063)	0.44 (0.017)	0.35 (0.061)	0.64 (**< 0.001**)
P2	0.17 (0.371)	0.51 (**0.005**)	0.30 (0.110)	0.59 (**0.001**)
P3	0.03 (0.882)	0.26 (0.180)	0.11 (0.567)	0.22 (0.244)
P4	0.23 (0.219)	0.25 (0.183)	0.16 (0.385)	0.36 (0.051)
P5	0.16 (0.397)	0.16 (0.409)	0.06 (0.749)	0.25 (0.179)
P6	0.03 (0.882)	0.21 (0.285)	0.04 (0.847)	0.16 (0.396)
P7	-0.00 (0.995)	0.32 (0.090)	0.14 (0.459)	0.28 (0.137)
P8	0.04 (0.838)	0.25 (0.193)	0.14 (0.454)	0.24 (0.197)
Overall NASA-TLX vs. % Incorrect responses				
	0.57 (**0.001**)	0.35 (0.056)	0.53 (**0.002**)	0.58 (**< 0.001**)

1

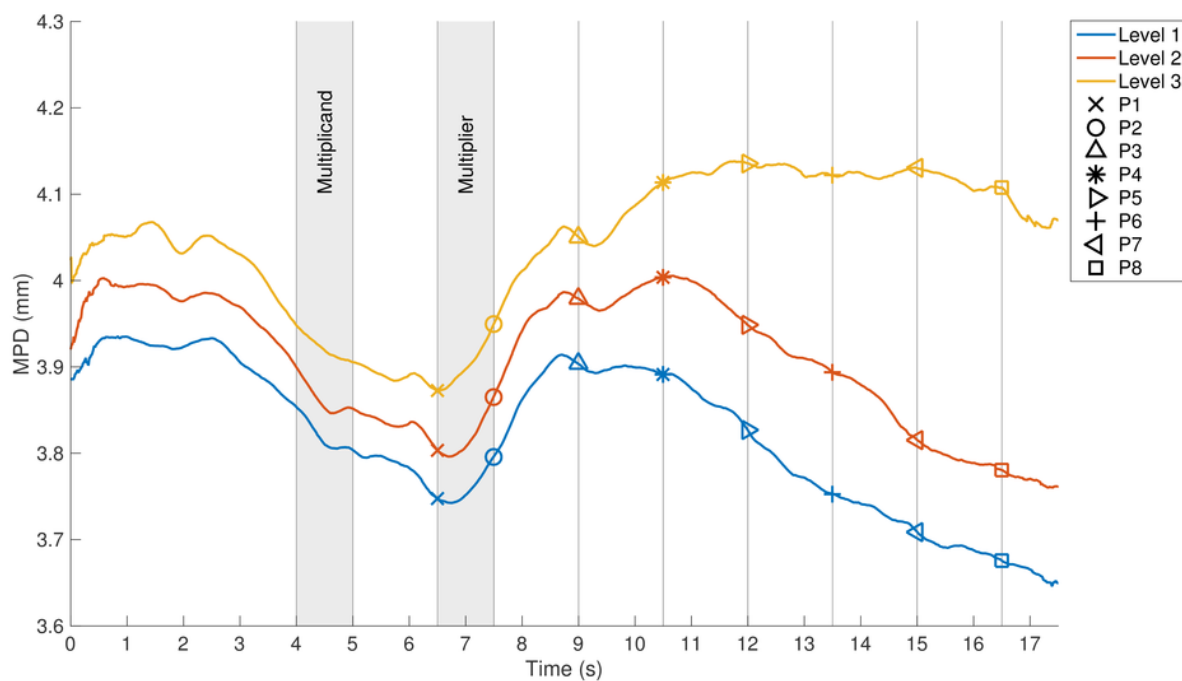
Experimental equipment: monitor with built-in eye-tracker (SmartEye DR120), chin-rest, and keyboard.

2

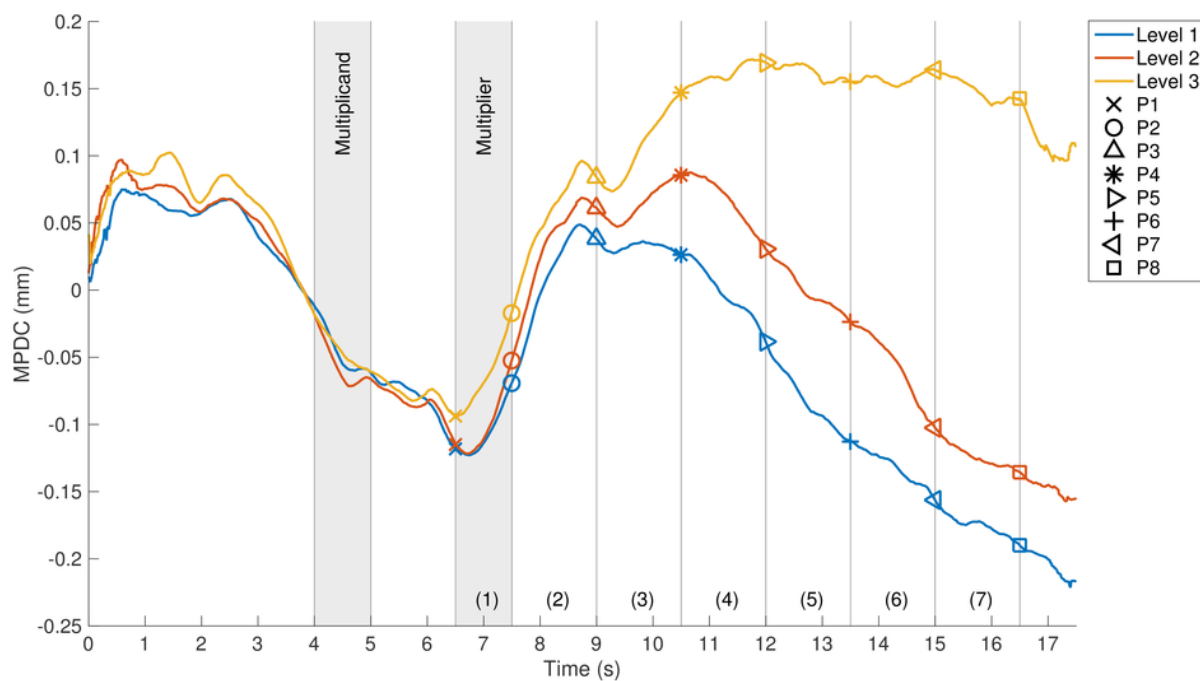
Task display during accommodation, pause, and calculation period.

Illustration of data processing. (A) Pupil diameter before and after linear interpolation for missing values. (B) Pupil diameter before and after linear interpolation for poor-quality data.

4

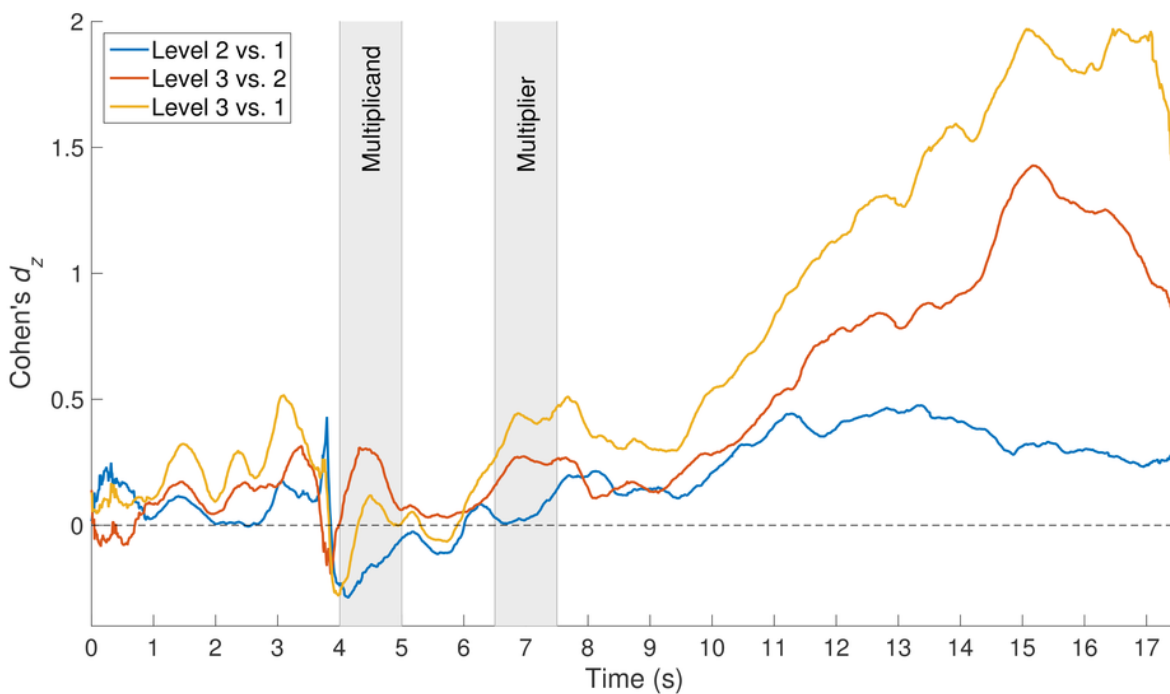
Mean pupil diameter (MPD) during the mental multiplication task, for the three levels of difficulty.

The grey bars represent the periods where the multiplicand and multiplier were shown on the screen. The numbers were masked by an "XX" during the remainder of the trial.

5

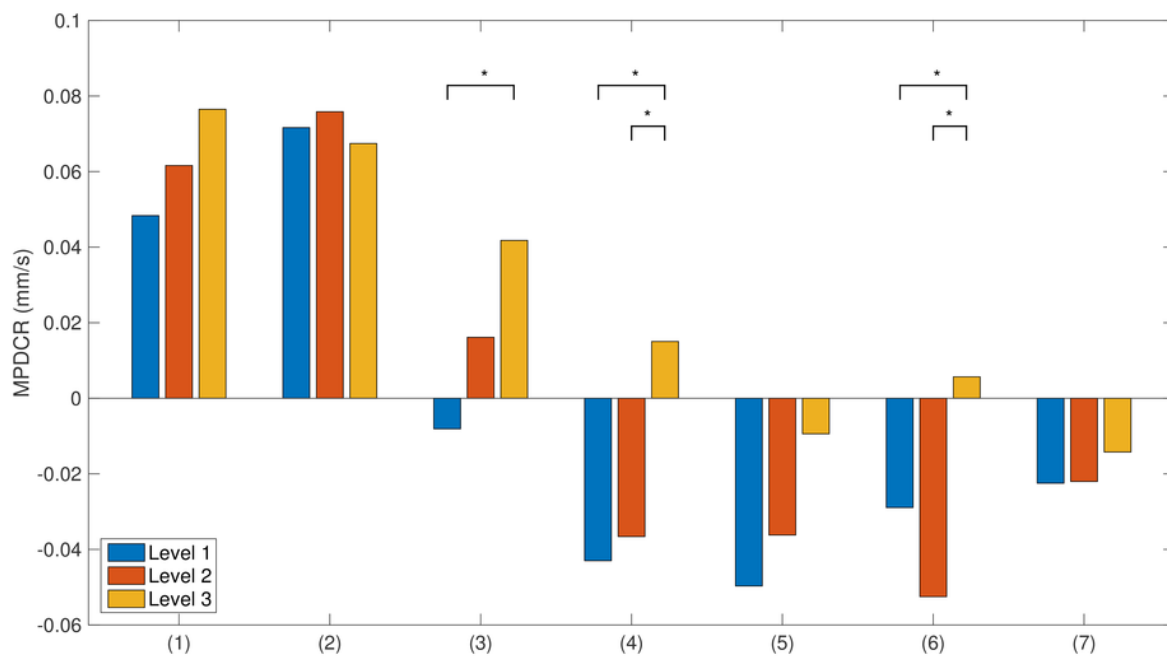
Mean pupil diameter change (MPDC) during the mental multiplication task, for the three levels of difficulty.

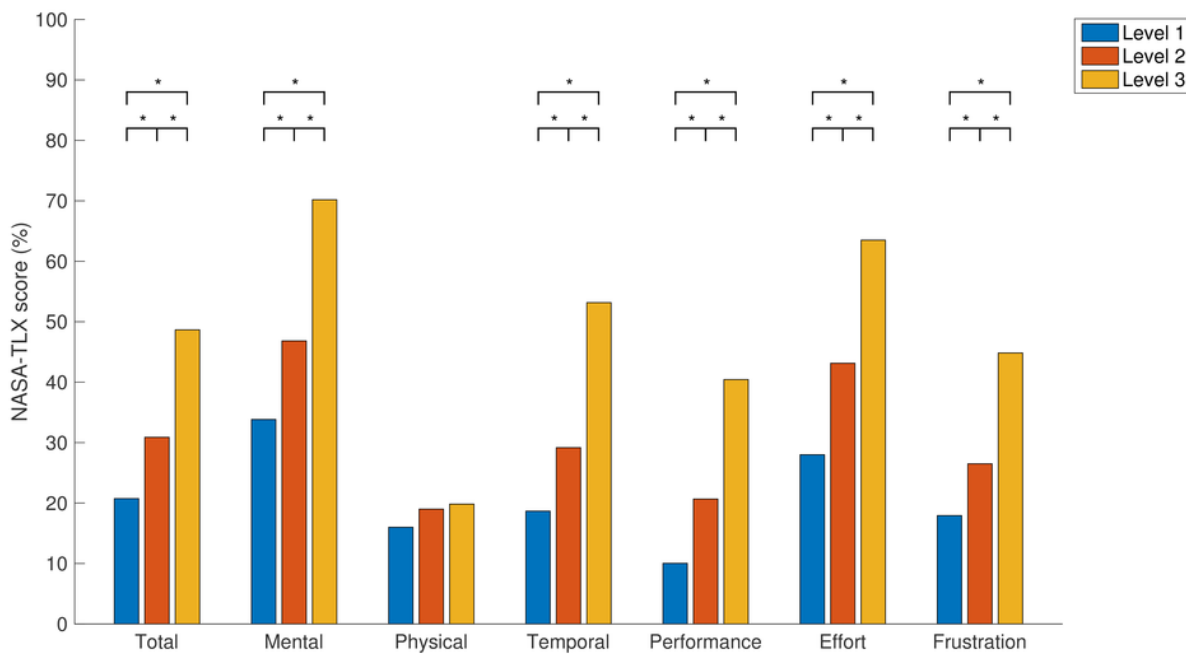
The grey bars represent the periods where the multiplicand and multiplier were shown on the screen. The numbers were masked by an "XX" during the remainder of the trial.

6

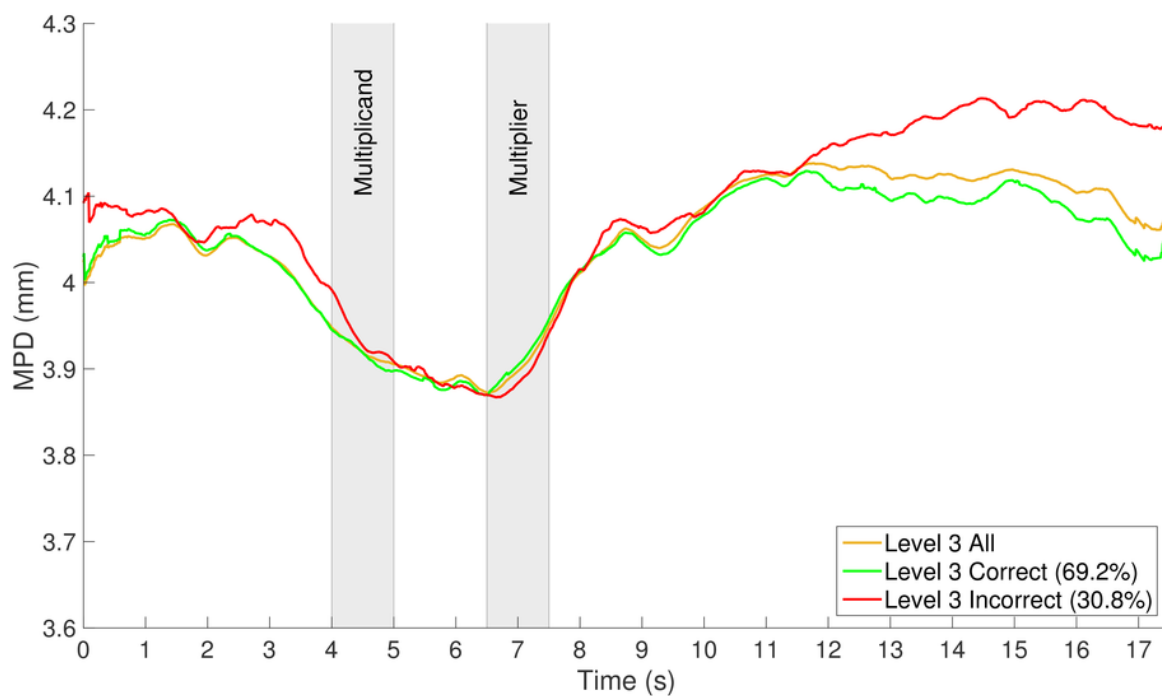
Cohen's d_z for the mean pupil diameter change (MPDC) between pairs of levels of difficulty.

The grey bars represent the periods where the multiplicand and multiplier were shown on the screen. The numbers were masked by an "XX" during the remainder of the trial.

7

Mean pupil diameter change rate (MPDCR), for the three levels of difficulty and for seven periods in time during the presentation of the multiplier and the calculation period.

The asterisks indicate statistically significant differences between the levels of difficulty.

Results of the NASA-TLX questionnaire, for the three levels of difficulty.

The asterisks indicate statistically significant differences between the levels of difficulty.

Mean pupil diameter (MPD) during the mental multiplication task, for the third level of difficulty. A distinction is made between correct and incorrect responses.

The grey bars represent the periods where the multiplicand and multiplier were shown on the screen. The numbers were masked by an "XX" during the remainder of the trial.

10

Mean cumulative number of blinks during the mental multiplication task, for the three levels of difficulty.