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Is accommodation a confounder in pupillometry research?

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ABSTRACT

Much psychological research uses pupil diameter measurements to investigate the cognitive and emotional effects of visual stimuli. A potential problem is that accommodating at a nearby point causes the pupil to constrict. This study examined to what extent accommodation is a confounder in pupillometry research. Participants solved multiplication problems at different distances (Experiment 1) and looked at line drawings with different monocular depth cues (Experiment 2) while their pupil diameter, refraction, and vergence angle were recorded using a photorefractor. Experiment 1 showed that the pupils dilated while performing the multiplications, for all presentation distances. Pupillary constriction due to accommodation was not strong enough to override pupil dilation due to cognitive load. Experiment 2 showed that monocular depth cues caused a small shift in refraction in the expected direction. We conclude that, for the young student sample we used, pupil diameter measurements are not substantially affected by accommodation.

1. Introduction

Pupillometry is an important research method in psychology. It became popular in the 1960s (e.g., Hess & Polt, 1960) and is currently widely used. A Scopus search shows that, in the year 2020 alone, 766 works were published with the words 'pupil diameter', 'pupil size', 'pupil dilation', or 'pupillometry' in their title, abstract, or keywords. Often, pupil diameter is measured to infer mental demands (Campbell, Toth, & Brady, 2018; Cohen Hoffing et al., 2020; Van der Wel & Van Steenbergen, 2018) or emotion while viewing pictorial stimuli (Henderson, Bradley, & Lang, 2018; Mckinnon, Gray, & Snowden, 2020; Nakakoga, Higashi, Muramatsu, Nakauchi, & Minami, 2020).

It is well known that pupil diameter is affected by the amount of light falling onto the retina. Therefore, it is imperative that light conditions are controlled in pupillometry research. Another potential confounder of pupil response is accommodation: as part of the pupillary near reflex, the pupil constricts when focusing on a nearby object (Alpern, Mason, & Jardinico, 1961; Marg & Morgan, 1950).

Accommodation is a feedback mechanism that counteracts the effects of image blur. This pathway begins with impulses sent from the optic nerve to the visual cortex, and from there to the Edinger-Westphal nucleus. Parasympathetic nerve fibres from the Edinger-Westphal nucleus synapse on the ciliary ganglion, the axons of which are short ciliary nerves that innervate the ciliary muscle and make it contract. This

contraction relaxes the tension of the lens's suspensory ligaments, making it more convex and increasing its optical power (Motlagh & Geetha, 2020). At the same time, the Edinger-Westphal nucleus sends impulses to parasympathetic nerve fibres, which, via the ciliary ganglion and short ciliary nerves, leads to the contraction of the iris sphincter muscle, which increases the depth of focus (Green, Powers, & Banks, 1980; Schwartz & Ogle, 1959).

For young adults, pupil diameter changes of 0.25–0.4 mm/D (where D stands for dioptre; 1 dioptre $=1\,\mathrm{m}^{-1}$) of accommodative response have been reported (Charman & Radhakrishnan, 2009; Kasthurirangan & Glasser, 2005; Schaeffel, Wilhelm, & Zrenner, 1993). Given these strong effects, Hunter, Milton, Lüdtke, Wilhelm, and Wilhelm (2000) cautioned that "the presence of strong correlations between changes in pupil size and lens accommodation would seriously limit the utility of measurements of pupil size fluctuations" (p. 567).

In pupillometry research, two accommodation mechanisms can be thought of. First, while participants are performing a mentally demanding task, they might shift their accommodation level. For example, participants may have difficulty staying focused on a visually-presented problem and start staring into the distance. Second, while participants view pictorial stimuli that contain apparent depth cues, they might shift their accommodation level in response to these cues. So far, however, most studies investigating the effect of mental demands on pupil size usually do not measure accommodation (e.g., Ahern & Beatty,

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1979; Klingner, 2010; Marquart & De Winter, 2015), and studies investigating the effect of apparent depth cues on accommodation or vergence typically do not report pupil size (e.g., Busby & Ciuffreda, 2005; Takeda, Hashimoto, Hiruma, & Fukui, 1999). Accordingly, there is only limited knowledge about the extent to which accommodation is a confounding variable in pupillometry research.

Vergence angle, that is, the inward rotation of the eyes driven by retinal disparity, is another important variable to consider, as vergence is part of the pupillary near reflex. Many studies have shown that pupil constriction is synchronised with vergence, a phenomenon that likely occurs via midbrain neurons that project to the Edinger-Westphal nucleus and oculomotor nucleus (Balaban, Kiderman, Szczupak, Ashmore, & Hoffer, 2018; Feil, Moser, & Abegg, 2017; Myers & Stark, 1990). According to the dual interaction model, the pupillary near reflex is not driven by accommodation or convergence independently but is an interactive outcome of the neural pathways that drive accommodation and vergence (see Fig. 15 in McDougal & Gamlin, 2015).

1.1. Effect of mental demands on accommodation

As pointed out above, accommodation could be a confounding factor in pupillometry studies that involve mentally demanding tasks. A small number of studies on this particular topic are available so far.

Hess and Polt (1964; $N = 5$) let participants solve verbally-presented multiplications problems while focusing on a screen at 1.45 m distance. They reported that participants' pupils dilated between about 10 % and 20 % while solving the multiplications. Next, participants were instructed to fixate on an object at a 99-cm or a 3.14-m distance. The authors reported that the mean pupil diameter was only 2.1 % larger when participants focussed on the distant object compared to the near object and therefore concluded that "accommodation was not a factor" (Hess & Polt, 1964, p. 1191). However, the authors did not present the time course of pupil diameter or other details that may be relevant to interpret their finding.

In the same vein, Kahneman and Beatty (1966; $N = 5$) complemented their pupillometry experiment on mental effort with trials in which participants performed a memory task while looking at a fixation target at a distance of 15 cm or 1.83 m. They performed these additional trials because participants reported the subjective feeling that their visual field became blurred while performing the memory task. Their results, presented as mean pupil diameter as a function of elapsed time, showed a strong accommodation effect, with the mean pupil diameter being about 0.4 mm larger for the 1.83-m than for the 15-cm distance. However, task-induced pupillary dilations of about 0.3 mm were present for both presentation distances. Therefore, Kahneman and Beatty concluded that "these results confirm Hess's conclusion that pupillary changes in mental activity are not mediated by changes of accommodation" (p. 155).

Several other studies have investigated the effect of mental demands on accommodation in closed-loop (i.e., normal viewing) conditions. Kruger (1980; $N = 20$ per group) found that performing a mental addition task led to an accommodation increase (i.e., a shift in focus towards a near point) compared to reading visually presented numbers. Malmstrom, Randle, Bendix, and Weber (1980; $N = 6$), on the other hand, reported that performing a counting backwards task while focusing on a visual target led to an accommodation decrease (i.e., towards a distant point) as compared to solely focusing on the target. According to Birnbaum (1984), these differences in results can be explained by visual demands: in Kruger, adding visually-presented numbers required participants to attended to the screen, whereas for the counting backwards task in Malmstrom et al., this was not needed. Research by Winn, Gilmartin, Mortimer, and Edwards (1991; $N = 10$) supports the notion that the degree of accommodation shift depends on the visual demands of the task. They used two mental tasks: one required the participants to focus on the screen by tracking the letter 'e' in four-letter arrays, and the other did not require focussing on the screen

as participants were counting backwards. Compared to a reference condition of just reading the letters, letter tracking led to an accommodation increase, whereas counting backwards did not significantly affect accommodation. More recently, Lalonde, Gehring, and Roberts (2018; $N = 21$) measured accommodation and pupil diameter simultaneously during mental tasks (adding numbers versus just reading numbers) and found that pupil diameter was larger for the mentally demanding task of adding up the numbers as compared to just reading the numbers. However, accommodation responses did not differ significantly between these two conditions.

The difficulty level of the task and the presentation distance may affect accommodation response. An effect of presentation distance on mental-demand-induced accommodation was reported by Bullimore and Gilmartin (1988; $N = 12$). They found that adding numbers shown at a very close (20 cm), medium (33.3 cm), and far (100 cm) distance led to, respectively, a decrease, no change, and an increase of accommodation as compared to just looking at these numbers. For a visual two-alternative forced-choice task, Davies, Wolffsohn, and Gilmartin (2005; $N = 16$) reported a reduction in accommodation (i.e., a shift in focus towards a distant point) with increasing mental demands. In Jainta, Hoormann, and Jaschinski (2008; $N = 40$ for Experiment 1 & 2, $N = 20$ for Experiment 3 & 4), accommodation and pupil diameter were measured simultaneously during various mentally demanding tasks (e. g., adding/multiplying numbers, n-back task). They observed task-induced pupil dilation but no significant association between mental demands and accommodation shift. However, they noted that their results might have been confounded by changes in the gaze direction during the cognitive tasks.

In summary, the different accommodation effects reported in the literature could be due to differences in visual demands and presentation distance. Moreover, only a few studies have measured accommodation and pupil diameter simultaneously during mentally demanding tasks.

1.2. Effect of apparent depth cues on accommodation

The second type of experiment in which pupil diameter may be affected by accommodation is an experiment in which two-dimensional pictorial stimuli are used for investigating pupillary response (e.g., Attard-Johnson & Bindemann, 2017; Finke, Deuter, Hengesch, & Schächinger, 2017; Mckinnon et al., 2020; Nakakoga et al., 2020; Snowden, McKinnon, Fitoussi, & Gray, 2019; Watts, Holmes, Savin-Williams, & Rieger, 2017). Such stimuli might contain monocular depth cues, which raises the question of whether apparent depth could trigger a change in accommodation or pupil diameter.

Takeda et al. (1999; $N = 5$) investigated the accommodative response of participants who shifted their focus between 'far' and 'near' points in paintings containing apparent depth cues. They reported that apparent depth elicited a strong accommodation response. In a similar study, Busby and Ciuffreda (2005; $N = 16$) measured accommodation responses while participants viewed images containing apparent depth cues (e.g., a straight road leading to the horizon). They found accommodation effects in the perceptually-appropriate direction, but these were small and mostly not statistically significant. Busby and Ciuffreda devoted several paragraphs to explaining why their effects differed from those of Takeda et al. In particular, they argued that eye movements could have confounded the effects found by Takeda et al.

Mizushina, Ando, Kochiyama, and Masaki (2009; $N = 3$) let participants look at an object presented at different distances, as well as photographs of the same scene. The results showed that accommodation and vergence changed as a function of the real presentation distance, but not for the corresponding photographs that were displayed at a constant distance, indicating that accommodation is affected by real depth, not apparent depth. In a more recent study, Koessler and Hill (2019; $N = 10$) investigated accommodation when looking at a hollow-mask illusion and found that participants accommodated to the perceived depth of the face rather than the real depth of the mask.

In Enright (1987; *N* = 9), participants were instructed to alternate their focus between the far and near corner of real and drawn boxes. The ocular convergence/divergence when focusing on near/far corners of the drawn boxes was consistent with, but attenuated from, vergence changes when looking at real boxes. However, pupillary constriction was not observed when looking at the near corner of the drawn box. Other studies have investigated whether distance perception in mental imagery can elicit an oculomotor response. Ruggieri and Alfieri (1992; *N* = 10), for example, found that accommodative responses when imagining near stimuli (e.g., reading a word in a book) versus far stimuli (e.g., seeing a ship in the horizon) were similar to those when looking at real stimuli.

In summary, it appears that apparent depth cues can elicit some changes in vergence and accommodation. However, more research is needed using concurrent measurements of eye-gaze angle, vergence, pupil diameter, and accommodation, to clarify the conflicting findings so far.

1.3. Study aim

According to the studies mentioned above, accommodation is not a major factor in pupillometry research. However, the number of studies is limited, and most studies do not report on pupil diameter and accommodation measured concurrently. Also, measurements of vergence angle should be included in pupillometry research. Additionally, much of the previous research used very small sample sizes. The landmark studies of Hess and Polt (1964) and Kahneman and Beatty (1966) used only five participants and did not use statistical testing of any sort.

In this paper, two experiments are presented, with 34 and 30 participants, respectively. The goal of the first experiment was to obtain reference values of pupil diameter, refraction, and vergence angle by letting participants perform cognitive tasks at three presentation distances: close (20 cm), halfway (70 cm), and far (180 cm). The first experiment was also meant to replicate the research of Hess and Polt (1964) and Kahneman and Beatty (1966) regarding the effects of cognitive load on pupil dilation for different presentation distances.

The second experiment aimed to investigate the effects of mental demands and apparent depth. Again, we expected that pupil diameter would increase in mentally demanding conditions, in accordance with much previous research (Ahern & Beatty, 1979; Hess & Polt, 1964; Kahneman & Beatty, 1966; Klingner, 2010; Marquart & De Winter, 2015), and we examined whether changes in refraction and vergence angle are associated with pupil diameter changes. Furthermore, we examined whether monocular depth cues cause a change in pupil diameter, accommodation, and vergence.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Thirty-six students from the TU Delft volunteered in the study. Two participants were excluded because of missing data for more than 50 % of the time (Laeng & Alnaes, 2019), with missing data defined as no recorded eye or refraction data for either eye, or horizontal or vertical eye movements greater than 30 deg. Accordingly, the data of 34 participants (17 females, 17 males) were retained. Twenty-eight of the included participants reported having no refraction error, five participants indicated a negative refraction error in both eyes (min. −2.5, max. −1.0), and one participant reported a positive refraction error in both eyes (+1.25 for the left eye, +1.5 for the right eye). Of the 28 participants who reported no refraction error, one reported astigmatism in one eye, and another participant reported amblyopia. No participants were excluded because of their refractive error or eye condition because our goal was to examine the research questions in a typical sample. The study was approved by the Human Research Ethics Committee of the TU

Delft. Each participant provided written informed consent.

2.1.2. Apparatus, software, and environmental conditions

The PowerRef 3 photorefractor (PlusOptix GmbH) was used to record participants' binocular eye movements, pupil diameter, and refraction at 50 Hz. The PowerRef 2 and 3 have been shown to provide congruent refraction measurements with other refractors (Aldaba, Gómez-López, Vilaseca, Pujol, & Arjona, 2015; Choi et al., 2000; Gehring, Lalonde, & Roberts, 2018). The PowerRef 3 was placed at a total path length of 1 m from the participants' eyes, which is according to the recommendations of the manufacturer (Plusoptix, 2019a). A head support was used to minimise the participants' head movements. The experimental setup is shown in Fig. 1.

During the experiment, an office lamp with dimmer was positioned to the right of the participant's head support. The orientation of the lamp and dimmer were adjusted to one of three pre-determined settings depending on the screen distance (20, 70, or 180 cm) to keep the illuminance constant (as measured with a Konica Minolta T-10MA positioned at the location of the participant's head and oriented towards the screen). The illuminance recordings made during the preparation of the experiment have not been preserved. However, after rebuilding the setup, we estimated that the illuminance during the experiment was between 3 and 5 lx.

Pupil diameter values were provided in millimetres (measurement range between 4.0 and 8.0 mm; resolution: 0.1 mm), refraction values were provided as spherical equivalent refraction (measurement range between +5.00 and −7.00 D), and horizontal and vertical gaze values were provided in degrees (resolution: 0.5 deg) (ranges as reported by the manufacturer; Plusoptix, 2019b). The pupil diameter per eye was provided as the average of the pupil width and the pupil height. The refraction values approximate the negative inverse of the focal length of the lens; thus, the closer the object, the more negative the refraction value, and the further away the object is, the more the negative refraction value moves towards 0 D (Hiura, Komine, Arai, & Mishina, 2018; Jainta, Jaschinski, & Hoormann, 2004).

A MATLAB script was used to present the stimuli. The stimuli were presented on a 19-inch LCD computer screen (HP Compaq LA1951 g, 1280 × 1024 pixels) with a refresh rate of 60 Hz. The setup was covered with a black curtain to block light from the room.

2.1.3. Stimuli and experimental design

Participants solved multiplication problems presented on the computer screen. Before the presentation of each multiplication, a control slide with a multiplication sign was shown for 10 s. Next, the multiplication was presented for 15 s. The multiplications were shown in a black outline Myriad Pro font of 2-pixel thickness, with a height of 10–12 % of the screen height and a width of 28–39 % of the screen width, on a background with a greyscale value of 50 %.

Table 1 shows the multiplications that were presented. The first independent variable was the difficulty level of the multiplications. The second independent variable was the distance between the participants' eyes and the screen: close (20 cm; viewing angle: 86.8 deg horizontal, 74.3 deg vertical), halfway (70 cm; viewing angle: 30.2 deg horizontal, 24.4 deg vertical), and far (180 cm; viewing angle: 12.0 deg horizontal, 9.6 deg vertical). The viewing distances were similar to Kahneman and Beatty (1966; 15 and 183 cm) and Jainta et al. (2004; 33, 50, and 100 cm).

The experiment consisted of three sessions. Each session consisted of nine multiplications (i.e., one set containing three problems per difficulty level) presented to the participant from one of the three viewing distances. The three viewing distances, as well as the presentation order of the three sets of multiplications and the nine multiplications per set, were randomised for each participant. At the end of the experiment, participants completed a questionnaire that included questions about their gender and refractive error.
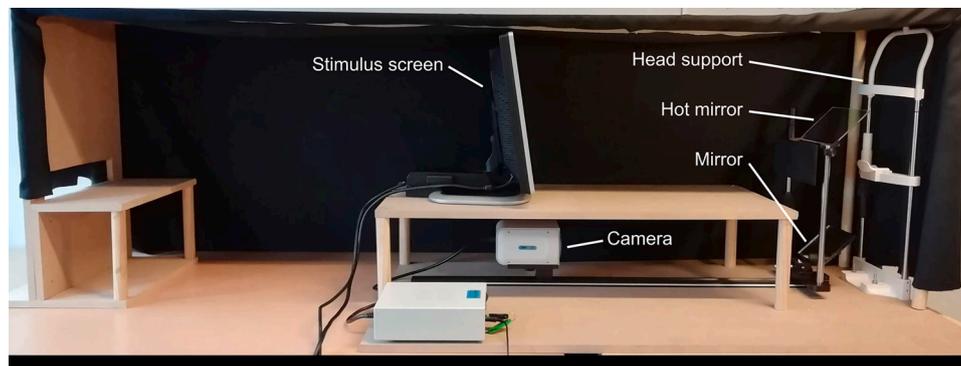
Fig. 1. Setup used in Experiment 1, with the computer screen at 70 cm viewing distance.

Table 1
Multiplication problems used in Experiment 1, categorised by their level of difficulty and presentation set.

	Easy	Medium	Hard
Set 1	8×13	13×14	15×17
	7×14	12×14	16×18
	6×16	9×17	13×18
	5×17	12×13	15×18
Set 2	6×14	8×18	14×16
	9×12	12×16	17×17
	5×16	9×16	13×17
Set 3	6×18	8×17	14×18
	7×13	12×13	15×15

2.1.4. Procedure and instructions

Participants were informed that the experiment aimed to examine the effect of accommodation on pupil size during a cognitively demanding task. After signing the consent form, participants placed their head in the head support and read the task instruction from the computer screen. The instruction informed the participants that first, only a cross would be shown, and that after 10 s, the multiplication would appear. Participants were asked to, once they had solved the multiplication, give their answer audibly. The instruction also stated that nine multiplications would appear, and that after that, the distance of the screen would change. Finally, the participants were asked to look at the screen while solving the multiplications and avoid communication with the experimenters. Upon completion of the first session, the experimenter changed the distance of the stimulus screen while the participants remained seated with their head in the head support. After the repositioning of the screen, the participants again read the instruction slide and performed the second session. The same procedure was repeated for the third session.

2.1.5. Data processing and analysis

Pupil diameter in mm, refraction in dioptres (D), and horizontal and vertical gaze angle data were exported from the PowerRef 3 and read in MATLAB. Missing data per variable were linearly interpolated (Kret & Sjak-Shie, 2019). Subsequently, data were filtered using a third-order low-pass Butterworth filter with a cut-off frequency of 5 Hz. Due to a recording error, the eye movements of participants were not measured for the last of the 27 multiplications.

Next, pupil diameter and refraction were averaged between the two eyes per time sample. Vergence was calculated as the difference between the horizontal gaze angle (i.e., gaze axis X) of the two eyes. A post-hoc correction was applied to all vergence angles by adding a constant offset of 11.2 deg (see Maiello, Kerber, Thorn, Bex, & Vera-Diaz, 2018, for a similar baseline vergence correction). We determined this value so that, for the farthest presentation distance of this experiment ($d = 180$ cm) and assuming an inter-pupillary distance (IPD) of 6.3 cm (Dodgson,

2004), the vergence angle corresponded with theoretical predictions, that is, vergence = 2*atan((IPD/2)/d).

Per presentation distance, an average of the three multiplications per difficulty level was taken per time sample for pupil diameter, refraction, and vergence angle. Next, the following dependent variables were calculated per trial, where one trial consisted of the presentation of a control slide for 10 s (0–10 s), followed by a stimulus slide for 15 s (10–25 s):

(1) Pupil diameter change (*PDC* in mm): The subtractive difference between the mean pupil diameter for the stimulus slide $\overline{PD}_{s,11-24}$ and the mean pupil diameter for the preceding control slide $\overline{PD}_{c,7.5-10}$. Subtractive baseline correction at the level of individual trials was also recommended by Mathôt, Fabius, Van Heusden, and Van der Stigchel (2018) and Reilly, Kelly, Kim, Jett, and Zuckerman (2019).

$$PDC = \overline{PD}_{s,11-24} - \overline{PD}_{c,7.5-10} \tag{1}$$

(2) Maximum pupil diameter change (*PDC_max* in mm): The difference between the maximum pupil diameter for the stimulus slide $\overline{PD}_{max,s,11-24}$ and the mean pupil diameter for the preceding control slide $\overline{PD}_c$.

$$PDC_{max} = \overline{PD}_{max,s,11-24} - \overline{PD}_{c,7.5-10} \tag{2}$$

(3) Pupil diameter change, responsive to mental demands (*PDC_resp* in mm): The difference between the mean pupil diameter for the stimulus slide $\overline{PD}_{s,15-24}$ and the mean pupil diameter for the preceding control slide $\overline{PD}_{c,7.5-10}$.

$$PDC_{resp} = \overline{PD}_{s,15-24} - \overline{PD}_{c,7.5-10} \tag{3}$$

(4) Refraction change (*RC* in D): The difference between the mean refraction for the stimulus slide $\overline{R}_{s,11-24}$ and the mean refraction for the preceding control slide $\overline{R}_{c,7.5-10}$.

$$RC = \overline{R}_{s,11-24} - \overline{R}_{c,7.5-10} \tag{4}$$

(5) Vergence angle change (*VAC* in degrees): The difference between the mean vergence angle for the stimulus slide $\overline{VA}_{s,11-24}$ and the mean vergence angle for the preceding control slide $\overline{VA}_{c,7.5-10}$.

$$VAC = \overline{VA}_{s,11-24} - \overline{VA}_{c,7.5-10} \tag{5}$$

(6) Percentage of correct responses (*CR*). Non-responses were clas-
sified as incorrect responses.

$\overline{PD}_{s,11-24}$, $\overline{R}_{s,11-24}$, and $\overline{VA}_{s,11-24}$, and $PDC_{max,s,11-24}$ were computed
between 11 and 24 s. That is, we omitted the first and the last 1 s of the
stimulus slides, consistent with Hess and Polt (1964) and De Winter,
Petermeijer, Kooijman, and Dodou (2021). A potential issue is that the
first few seconds of pupil diameter follow a similar pattern regardless of
mental demand (e.g., Marquart & De Winter, 2015). Therefore, we also
computed $\overline{PD}_{s,15-24}$ by taking the mean of the pupil size between 15 and
24 s, thus excluding the dilation onset. Accordingly, PDC_{resp} is intended
to be more responsive to mental demands than PDC.

$\overline{PD}_{c,7.5-10}$, $\overline{R}_{c,7.5-10}$, and $\overline{VA}_{c,7.5-10}$ were computed between 7.5 and
10 s (De Winter et al., 2021; Hess & Polt, 1964). We used the last 2.5 s of
control slide to compute the baseline to avoid including possible effects
from the preceding stimulus. There are examples in the literature where
a shorter baseline period has been used (e.g., 0.4 s in Klingner, 2010, 1 s
in Geangu, Hauf, Bhardwaj, & Bentz, 2011). However, averaging over a
longer baseline duration is preferable when the mean pupil diameter has
become stable as it is more robust to noise in the pupil diameter re-
cordings (De Winter et al., 2021).

Statistical comparisons were conducted at the level of participants.
The dependent variables were subjected to two-way repeated-measures
ANOVAs to examine the effects of presentation distance and difficulty.
Post-hoc comparisons between the three difficulty levels were per-
formed using paired-samples *t*-tests for *PDC*, PDC_{max}, PDC_{resp}, *RC*, and
VAC, and using signed-rank tests for *CR*. A significance level of .05 was
used, and in the case of paired comparisons between the three difficulty
levels, a Bonferroni correction was used ($\alpha = .05/3 \approx .017$).

2.2. Results

Fig. 2 (left) shows the mean pupil diameter per difficulty level and
distance as a function of time. The pupil diameter was smaller when the
screen was closer to the participants' eyes. The corresponding mean
pupil diameter sensitivity, as measured for the baseline period (i.e.,
7.5–10 s) between the close and far distance, was 0.55 mm/D ($SD = 0.43$
mm/D, $N = 34$). Fig. 2 (left) also shows a considerable dilation after the
presentation of the multiplication, this dilation being stronger when the
screen was closer and when the multiplication was harder.

Fig. 2 (middle) shows the mean refraction, which differed strongly
between the three presentation distances. For the close distance, the
multiplication caused the refraction values to become more negative
than baseline, which indicates a shift in focus towards a near point.

Fig. 2 (right) shows the mean vergence angle. The vergence angle
differed strongly between the three distances, with the close presenta-
tion causing the highest vergence angle.

Table 2 shows the results of two-way repeated-measures ANOVAs for
multiplication level and distance, and Table 3 shows the corresponding
means and standard deviations and results of pairwise comparisons.
PDC, PDC_{max}, and PDC_{resp} increased significantly with difficulty and
decreased with distance, with PDC_{resp} (which excluded the first 5 s of
dilation) being the most sensitive to the effect of multiplication diffi-
culty. Pairwise comparisons showed that these three pupil dilation
measures increased significantly with multiplication difficulty for the
halfway presentation distance only. *RC* and *VAC* were significantly
associated with distance but not with difficulty. Furthermore, *CR*
decreased with increasing difficulty (Table 3). None of the Difficulty x
Distance interactions were significant.

2.3. Discussion

Experiment 1 aimed to determine pupil diameter, refraction, and
vergence angle in a mentally demanding task. Participants solved

Table 2
Results of statistical comparisons in Experiment 1.

	Difficulty	Distance	Interaction
PDC (mm)	$F_{(2, 66)} = 4.94$, $\boldsymbol{p =}$ $\textbf{.010}$, $\eta_p^2 = .13$	$F_{(2, 66)} = 20.58$, $\boldsymbol{p}$ $\boldsymbol{< .001}$, $\eta_p^2 = .38$	$F_{(4, 132)} = 0.74$, $p =$ .567, $\eta_p^2 = .02$
PDC_{max} (mm)	$F_{(2, 66)} = 3.76$, $\boldsymbol{p =}$ $\textbf{.028}$, $\eta_p^2 = .10$	$F_{(2, 66)} = 27.06$, $\boldsymbol{p}$ $\boldsymbol{< .001}$, $\eta_p^2 = .45$	$F_{(4, 132)} = 0.95$, $p =$ .435, $\eta_p^2 = .03$
PDC_{resp} (mm)	$F_{(2, 66)} = 7.85$, $\boldsymbol{p <}$ $\boldsymbol{.001}$, $\eta_p^2 = .19$	$F_{(2, 66)} = 22.44$, $\boldsymbol{p}$ $\boldsymbol{< .001}$, $\eta_p^2 = .40$	$F_{(4, 132)} = 0.91$, $p =$ .458, $\eta_p^2 = .03$
RC (D)	$F_{(2, 66)} = 1.98$, $p =$ .147, $\eta_p^2 = .06$	$F_{(2, 66)} = 10.64$, $\boldsymbol{p}$ $\boldsymbol{< .001}$, $\eta_p^2 = .24$	$F_{(4, 132)} = 0.34$, $p =$ .848, $\eta_p^2 = .01$
VAC (deg)	$F_{(2, 66)} = 3.06$, $p =$ .054, $\eta_p^2 = .08$	$F_{(2, 66)} = 9.77$, $\boldsymbol{p <}$ $\boldsymbol{.001}$, $\eta_p^2 = .23$	$F_{(4, 132)} = 1.78$, $p =$ .136, $\eta_p^2 = .05$

Note. Statistically significant *p*-values are indicated in boldface.
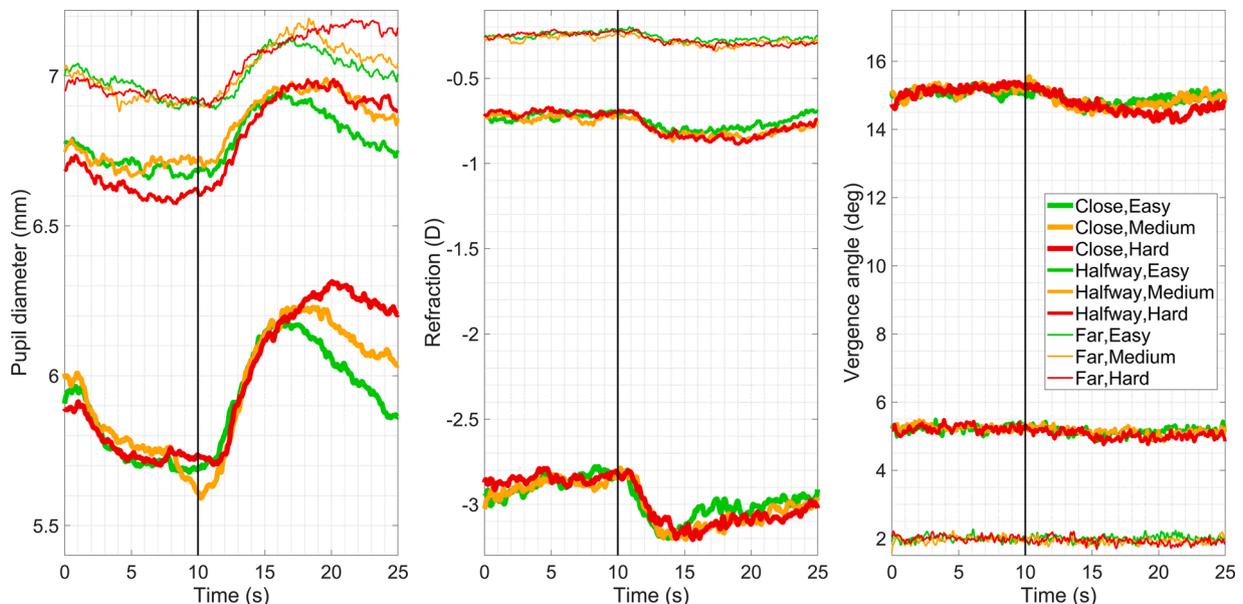
Fig. 2. Results of Experiment 1. Left: Mean pupil diameter. Middle: Mean refraction. Right: Mean vergence angle. The black vertical line at 10 s indicates the
transition from the control slide to the multiplication slide. A more negative refraction value corresponds to an increase in accommodation.

Table 3

Mean (SD) of the dependent variables for the three difficulty levels and three distances, and results of statistical comparisons in Experiment 1 ($df = 33$ for paired t-tests).

	1. Easy Mean (SD)	2. Medium Mean (SD)	3. Hard Mean (SD)	1 vs. 2 t / Z	p	1 vs. 3 t / Z	p	2 vs. 3 t / Z	p
Close									
PDC (mm)	0.330 (0.270)	0.386 (0.343)	0.397 (0.307)	−1.09	.283	−1.06	.297	−0.16	.873
PDC_{max} (mm)	0.788 (0.365)	0.846 (0.431)	0.850 (0.395)	−0.98	.333	−0.85	.403	−0.06	.955
PDC_{resp} (mm)	0.375 (0.304)	0.471 (0.408)	0.505 (0.348)	−1.62	.115	−1.78	.085	−0.44	.662
RC (D)	−0.228 (0.326)	−0.212 (0.293)	−0.241 (0.357)	−0.44	.662	0.36	.722	0.93	.357
VAC (deg)	−0.221 (1.187)	−0.449 (0.675)	−0.669 (0.747)	1.08	.289	1.91	.065	1.76	.087
CR (%)	94.1 (15.3)	82.4 (24.9)	62.8 (35.6)	2.55	**.011**	3.88	**<.001**	3.19	**.001**
Halfway									
PDC (mm)	0.168 (0.121)	0.188 (0.148)	0.287 (0.209)	−0.87	.390	−4.09	**<.001**	−2.94	**.006**
PDC_{max} (mm)	0.519 (0.186)	0.526 (0.185)	0.646 (0.278)	−0.29	.722	−3.59	**.001**	−2.97	**.006**
PDC_{resp} (mm)	0.186 (0.140)	0.221 (0.169)	0.343 (0.225)	−1.27	.211	−4.45	**<.001**	−3.25	**.003**
RC (D)	−0.071 (0.143)	−0.080 (0.107)	−0.116 (0.150)	0.55	.586	2.77	**.009**	1.75	.089
VAC (deg)	−0.156 (0.459)	−0.103 (0.435)	−0.197 (0.416)	−0.53	.597	0.43	.668	1.28	.209
CR (%)	95.1 (12.0)	81.4 (24.9)	59.8 (37.4)	2.98	**.003**	4.09	**<.001**	2.90	**.004**
Far									
PDC (mm)	0.131 (0.138)	0.159 (0.139)	0.182 (0.157)	−0.86	.399	−1.86	.072	−0.88	.385
PDC_{max} (mm)	0.458 (0.154)	0.495 (0.174)	0.505 (0.193)	−1.04	.304	−1.60	.119	−0.33	.741
PDC_{resp} (mm)	0.160 (0.162)	0.195 (0.166)	0.225 (0.185)	−0.93	.358	−2.08	.045	−0.96	.342
RC (D)	−0.044 (0.085)	−0.037 (0.075)	−0.058 (0.082)	−0.45	.658	1.00	.324	1.52	.138
VAC (deg)	0.045 (0.384)	−0.093 (0.347)	−0.079 (0.332)	2.52	.017	1.77	.087	−0.20	.839
CR (%)	95.1 (12.0)	85.3 (27.5)	52.9 (34.0)	2.23	.026	4.48	**<.001**	4.11	**<.001**

Note. A positive PDC means that the pupil dilated compared to the control slide. A negative RC means that the refraction became more negative (i.e., more accommodation) compared to the control slide. A negative VAC means that the vergence angle decreased compared to the control slide. The t / Z columns depict the t-statistics from the paired t-tests and Z-values from the signed-rank test (the latter used for CR only). Statistically significant p-values are indicated in boldface.

multiplications presented at three distances: close, halfway, and far. Experiment 1 was a replication of Hess and Polt (1964) and Kahneman and Beatty (1966), who reported that pupil dilation could be detected regardless of presentation distance.

The results showed that the pupil diameter was smaller when the screen was closer to the participants' eyes. Whether this effect is due to the near reflex (i.e., a nearby screen causes pupil constriction due to accommodation) or represents a tonic constriction in response to luminance (i.e., a nearby screen causes more light to fall onto the participants' retina, despite our illuminance control) cannot be established conclusively. The pupil diameter for the control slide changed with 0.55 mm/D, which is stronger than the accommodative responses of 0.25 to 0.4 mm/D reported in the literature (see Introduction). This suggests that the near reflex and the luminance effect both contributed to pupil constriction.

The participants' pupils dilated for all three distances, a finding that replicates Hess and Polt (1964) and Kahneman and Beatty (1966). However, we found that the closer the screen, the larger the dilation. For example, PDC values for the hard multiplications were 0.182, 0.287, and 0.397 mm for the far, halfway, and close distances. The mean refraction change relative to baseline (RC) for the close presentation condition was −0.21 D to −0.24 D. In other words, when the screen was presented nearby, participants increased accommodation relative to baseline, presumably in an attempt to read the multiplication from the screen. For an RC value of −0.24 D, a pupil constriction of 0.1 mm would be expected (i.e., assuming 0.4 mm/D). We observed a pupil dilation of 0.397 mm instead, suggesting that the effects of cognitive load were strong enough to override the effects of accommodation. Similarly, the vergence angle changes relative to baseline (VAC) were small, with the largest effect being −-0.7 deg (i.e., a reduction of vergence) for the hard multiplications and close presentation condition. In comparison, the vergence angle for the close presentation condition was approximately 15 deg (see Fig. 2).

The smaller pupil dilation for the larger presentation distance can be explained by low luminance when the screen is far away. Our baseline pupil diameter in the far condition was as high as 7 mm. In comparison, the dark-adapted pupil diameter is on average about 7.3 mm ($SD = 0.8$ mm) in young persons (20–29 years; Bradley, Bentley, Mughal,

Bodhireddy, & Brown, 2011; Winn, Whitaker, Elliott, & Phillips, 1994). Research indicates that pupil dilation in response to cognitive load is similar for different luminance levels (Bradshaw, 1969; Peysakhovich, Vachon, & Dehais, 2017; Reilly et al., 2019). However, in dark-adapted conditions, the pupillary response might reduce. Steinhauer, Siegle, Condray, and Pless (2004) measured the pupil responses of participants performing a mentally demanding task in a lit room and darkness and found that pupil dilation was larger in the lit room compared to darkness, which is consistent with our findings. The negative correlations between participants' baseline pupil diameter ($\overline{PD_c}$) and pupil diameter change values (PDC) provide further support for this thesis (see Supplementary Material).

Of note, our photorefractor was able to measure pupil diameters up to 8 mm only (Plusoptix, 2019a). However, an analysis of missing data (see Fig. S1 in the Supplementary Material) suggests that the measurement range of the photorefractor was not a factor that could explain the reduced pupillary sensitivity for increasing presentation distance.

The lack of a significant effect between the three difficulty levels for the closest distance could be due to extraneous influences entering the measurements. As could be seen in Table 3, the standard deviations for the close distance were higher than for the halfway and far presentation distances. This variability may have been because a nearby screen requires large horizontal eye movements to read the multiplication. In addition, participants may have had difficulty accommodating consistently for the close presentation distance.

3. Experiment 2

Experiment 1 provided a successful replication of the work of Hess and Polt (1964) and Kahneman and Beatty (1966) regarding pupil dilation at different presentation distances (0.2 m, 0.7 m, and 1.8 m). Furthermore, Experiment 1 offered reference values regarding pupil dilation, refraction, and vergence. In Experiment 2, we replicated the results of Experiment 1 for one presentation distance of 1 m, with additional measurements of response time and tightly controlled luminance conditions (Task 1), and we examined the effects of monocular depth cues on pupil dilation (Task 2).

3.1. Methods

3.1.1. Participants

Thirty-six students from the TU Delft volunteered in Experiment 2. None of the participants had taken part in Experiment 1. Six participants were excluded because of missing data for more than 50 % of the time. Accordingly, data for 30 participants (12 females, 18 males) with a mean age of 22.07 ($SD = 1.70$) years were retained. Twenty-one participants reported having no refraction error, eight participants reported a negative refraction error of both eyes (min. −6.0, max. −0.25), and one participant reported mixed values (−0.25 for the left eye, +0.75 for the right eye). Four participants wore contact lenses during the experiment. Thirteen participants reported having blue eyes, ten participants brown, four participants green, two green/brown, and one grey. The study was approved by the Human Research Ethics Committee of the TU Delft. Each participant provided written informed consent.

3.1.2. Apparatus, software, and environmental conditions

The PowerRef 3 photorefractor was again used to record participants' binocular eye movements, pupil diameter, and refraction at 50 Hz. The experimental setup is shown in Fig. 3.

A MATLAB script was used to present the stimuli, send time markers to the photorefractor, and record reaction time data from keyboard inputs. The visual stimuli were presented on a 24-inch LCD computer screen (BenQ 24" XL2420Z, 1920 × 1080 pixels) with a refresh rate of 60 Hz, located at a 1-m distance from the eyes. For this distance, the display subtended a 29.8 deg horizontal and 16.5 deg vertical viewing angle. The luminance of the screen was 5.6 cd/m^2, measured by pointing the sensor (Konica Minolta LS-150) through the hot mirror towards the screen (see Fig. 1 for the location of the hot mirror). There was no natural light in the room. The room was illuminated by a desk lamp located behind the participant and pointing to the back wall. The illuminance of the lighting in the room near the participant's eyes was 3.3 lx or 1.7 lx with the sensor (Konica Minolta T-10MA) oriented towards the ceiling or towards the screen, respectively. Low-light conditions were chosen because external light seemed to interfere with the functioning of the photorefractor. The participants wore closed-back headphones (Beyerdynamic DT-770 Pro 32 Ohm) to block sounds from the environment.

3.1.3. Stimuli and experimental design

Experiment 2 consisted of two tasks. In Task 1, nine multiplication problems were presented on the computer screen. Before the presentation of each multiplication, a control slide with a multiplication sign was shown for 10 s. Next, the multiplication was shown for a duration of 15 s. The multiplications were similar to previous pupillometry studies (Ahern & Beatty, 1979; Marquart & De Winter, 2015) and were categorised into three levels of difficulty (Table 4). The multiplications were shown in black outline Mangal font of 2-pixel thickness with a height corresponding to 10 % of the screen height and a width corresponding to 26–30 % of the screen width, on a background with a greyscale value of 50 %.

For Task 2, a ball was shown that moved from the bottom to the middle of the screen, and back to the bottom. One movement of the ball lasted 6 s and was discontinuous or continuous. The discontinuous movement consisted of two jumps from the bottom to the middle of the screen with 1-s intervals between the jumps and a 2-s pause when the ball had reached the middle of the screen, followed by two jumps from the middle to the bottom of the screen (Fig. 4). The continuous movement consisted of a fluent movement from the bottom towards the middle of the screen and back. The distinction between discontinuous and continuous movement was made to investigate whether the movement type causes different viewing patterns and accommodation shifts. More specifically, the discontinuous movement would allow for intermittent fixations, whereas the continuous movement would be expected to cause smooth pursuit. Before the presentation of each moving ball, a control slide showing only the ball at the bottom of the screen was shown for 10 s (Fig. 5, top left).

The ball movement was combined with four levels of monocular depth cues, as shown in Fig. 5. Line drawings were used to keep overall luminance levels as constant as possible according to recommendations by Janisse (1977, p. 7) and Sirois and Brisson (2014). Level 1

Table 4
Multiplication problems used in Task 1 of Experiment 2, categorised by their level of difficulty.

Easy	Medium	Hard
6 × 12	8 × 16	14 × 17
7 × 14	9 × 14	16 × 18
8 × 13	11 × 13	15 × 16

Fig. 3. Setup used in Experiment 2. Left: Setup in regular lighting conditions. Right: Setup in the lighting conditions of the experiment. The wooden structure was used for a test measurement for each participant and was removed before Task 1.
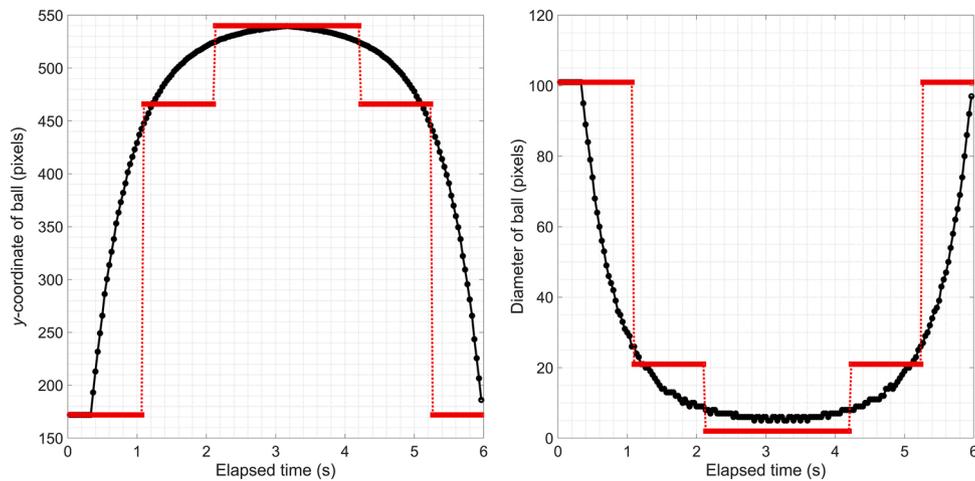
Fig. 4. Discontinuous (red) and continuous (black) movement of the moving ball presented in Task 2 of Experiment 2. The left figure depicts the height of the ball on the screen, where 1 is the bottom of the screen, and 1080 is the top of the screen. The right figure depicts the diameter of the ball. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).
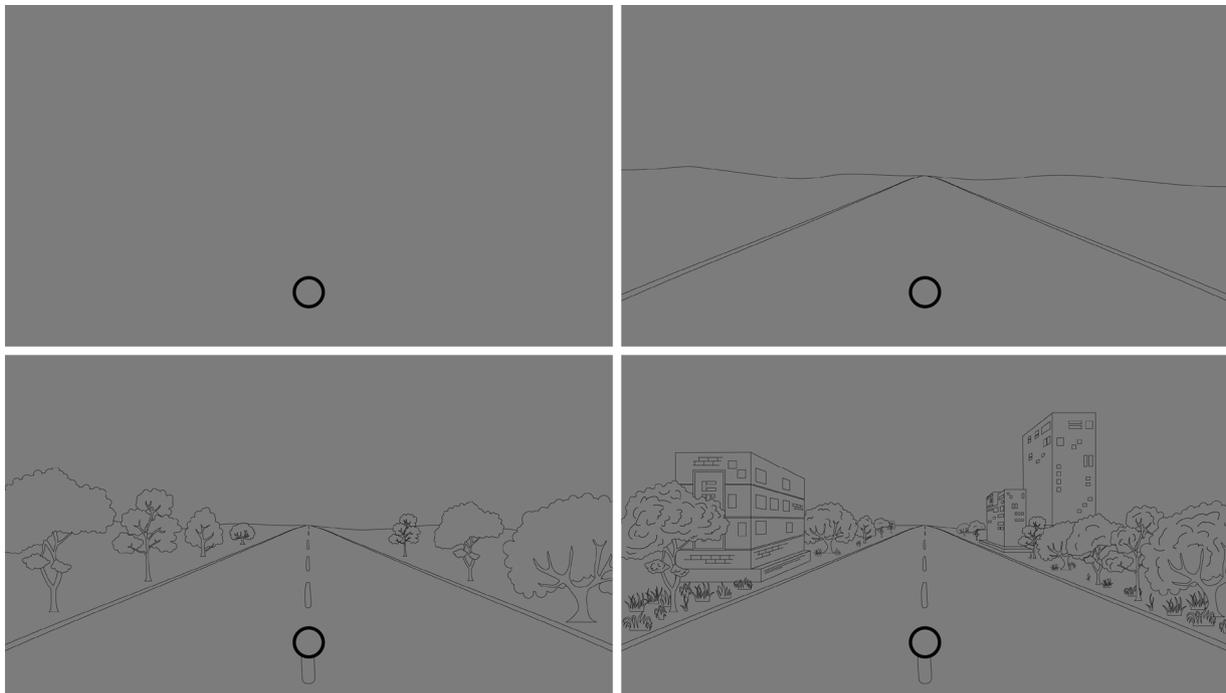
Fig. 5. Depth cue levels, from Level 1 (top left) to Level 4 (bottom right), used in Task 2 of Experiment 2.

incorporated only the depth cue from the change in the size of the ball during its vertical motion. For Level 2, linear perspective was added, Level 3 also included relative size, and Level 4 also provided occlusion and atmospheric perspective. It was expected that with more depth cues, the upward movement of the ball towards the virtual depth of the image (i.e., the far point on the horizon) would cause a decrease in accommodation.

All images consisted of black outlines of 1-pixel thickness on a grey background with a greyscale value of 50 %. Eight videos (2 movement types x 4 depth cue levels) were shown at a frame rate of 30 frames per second. These eight videos were randomised three times separately and concatenated, resulting in 24 videos per participant.

3.1.4. Procedure and instructions

Participants were informed that the experiment aimed to investigate whether accommodation, pupil size, and vergence are influenced by

mental workload and the illusion of depth. After signing the consent form, participants completed a questionnaire about their gender, age, eye colour, refractive error per eye, and whether they were wearing contact lenses. Next, participants placed their head in the head support and performed a test measurement in which they alternated their focus on two parts of a wooden object (Fig. 3). After the test measurement, the results of which are not used, the wooden object was removed, and the participants read the written instructions for Task 1 on the screen. The instruction informed the participants that their aim was to solve nine multiplications. It was mentioned that at first only the multiplication sign would be shown, that after 10 s the multiplication would appear and that they had 15 s to solve the multiplication. Participants were asked to press the spacebar once they had solved the multiplication and give their answer audibly. For Task 2, the instruction informed the participants that they had to keep their focus on a ball, which would move over the screen in a series of 24 movements. They were informed

that first, only the ball would be shown and that, after 10 s, the ball would move for 6 s.

3.1.5. Data processing and analysis

Data were processed as in Experiment 1. For Task 1, an average of the three multiplications per difficulty level was taken per time sample for pupil diameter, refraction, and vergence angle. For Task 2, an average of the three repetitions of each combination of level of depth cues and movement type was taken per time sample. For Task 1, $\overline{PD}_s$, $\overline{PD}_{s,max}$, $\overline{PD}_{s,resp}$, $\overline{R}_s$, and $\overline{VA}_s$ were computed for the same intervals as in Experiment 1. For Task 2, $\overline{PD}_s$, $\overline{R}_s$, and $\overline{VA}_s$ were computed between 12.5 and 13.5 s (i.e., top location of the ball). For both tasks, $\overline{PD}_c$, $\overline{R}_c$, and $\overline{VA}_c$ were computed between 7.5 and 10 s, as in Experiment 1. Next to the dependent variables described in Experiment 1, the response time (RT in seconds) was calculated for Task 1. If no response was provided within the allocated time of 15 s, a RT value of 15 s was used.

Statistical comparisons were conducted for Tasks 1 and 2 at the level of participants. For Task 1, the effect of difficulty level on the dependent variables was assessed using one-way repeated-measures ANOVAs. Paired comparisons for Task 1 were conducted using paired-samples *t*-tests for PDC, PDC_{max}, PDC_{resp}, RC, VAC, and RT and signed-rank tests for CR. For Task 2, two-way repeated-measures ANOVAs were conducted to examine the effects of depth cues and movement type on PDC, RC, and VAC. A significance level of .05 was used, and a Bonferroni correction was used for the paired comparisons between the three difficulty levels ($\alpha = .05/3 \approx .017$).

3.2. Results

3.2.1. Task 1 – solving multiplication problems

Fig. 6 (left) shows the mean pupil diameter of participants per difficulty level as a function of time. The pupil diameter started increasing after the presentation of the multiplication. The hard multiplications took more time to solve (see RT in Table 5) and resulted in a more sustained dilation than the easy and medium ones. Fig. 6 further shows the mean refraction (middle) and mean vergence angle (right) of participants. It can be seen that the refraction and vergence angle were relatively constant.

Table 5 shows the means and standard deviations of the dependent

variables for the three multiplication levels, and results of the statistical tests. PDC, PDC_{max}, PDC_{resp}, and RT were significantly affected by difficulty level, yielding higher values for the hard multiplications than for the easy ones. As in Experiment 1, PDC_{resp} was a more sensitive index of pupil dilation than PDC and PDC_{max}. CR decreased with increasing difficulty level. RC was weakly influenced by difficulty level, with the hard multiplications yielding a shift towards a more nearby point. For VAC, no significant effects were observed.

3.2.2. Task 2 – looking at line drawings with monocular depth cues

Fig. 7 (left) shows the mean pupil diameter of participants per combination of movement type and level of depth cues. For the continuous ball movement, participants' pupils on average constricted during the first 1.5 s of the video, followed by slow re-dilation. Pupil diameter for the discontinuous ball motion lagged behind pupil diameter for the continuous ball motion, which is consistent with the ball's change in *y*-coordinate, as shown in Fig. 4. A two-way repeated-measures ANOVA showed that PDC was not significantly associated with depth cues ($F(3, 87) = 1.56$, $p = .205$, $\eta_p^2 = .05$) or movement type ($F(1, 29) = 1.91$, $p = .177$, $\eta_p^2 = .06$). Furthermore, there was no significant interaction between depth cues and movement type ($F(3, 87) = 2.24$, $p = .089$, $\eta_p^2 = .07$).

Fig. 7 (middle) shows that refraction became more negative by approximately 0.2 D during the ball's upward movement and became less negative when the ball moved downwards. Participants' RC was significantly associated with depth cues ($F(3, 87) = 5.53$, $p = .002$, $\eta_p^2 = .16$) but not with movement type ($F(1, 29) = 0.19$, $p = .666$, $\eta_p^2 < .01$). Furthermore, no significant interaction was found between depth cues and movement type ($F(3, 87) = 1.63$, $p = .188$, $\eta_p^2 = .05$). The overall mean (*SD*) RC was -0.255 (0.232), -0.260 (0.238), -0.258 (0.220) and -0.198 (0.247) for Level 1–4 depth cues for the continuous movement, and -0.281 (0.253), -0.245 (0.218), -0.238 (0.202) and -0.229 (0.223) for Level 1–4 for the discontinuous movement. In other words, it appears that the Level 4 depth cues were associated with accommodation towards a farther point (i.e., an RC value that is more towards the positive).

Fig. 7 (right) shows that the vergence angle decreased slightly with the ball's upward movement and increased slightly again once the ball
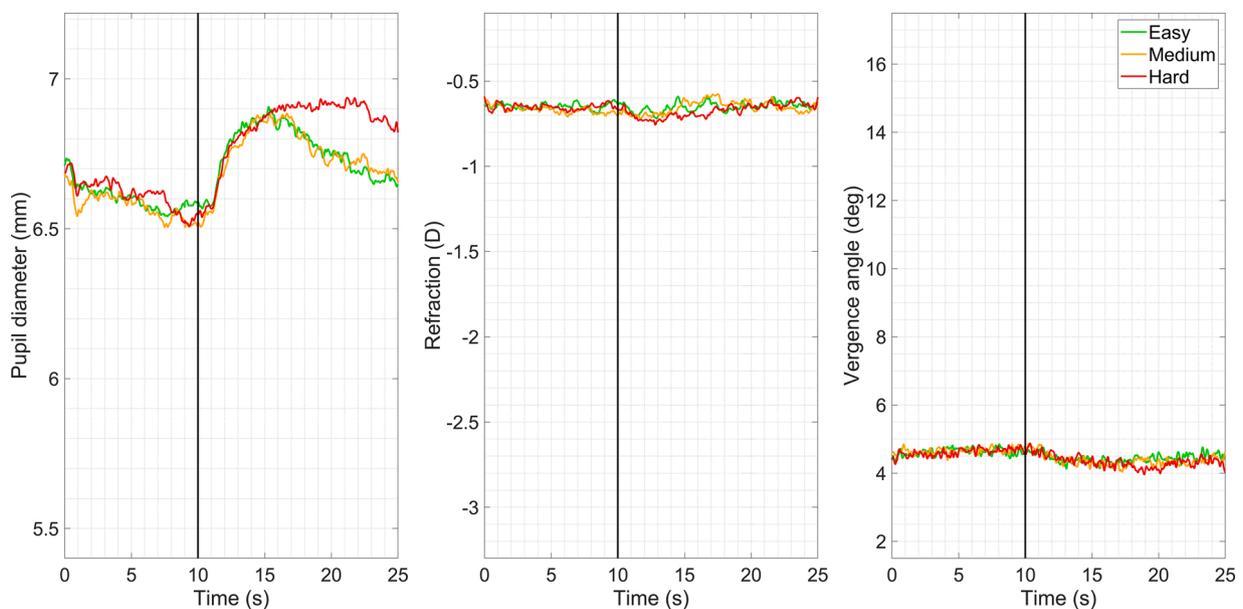
Fig. 6. Results for Task 1 of Experiment 2. Left: Mean pupil diameter. Middle: Mean refraction. Right: Mean vergence angle. The black vertical line at 10 s indicates the transition from the control slide to the multiplication slide. A more negative refraction value corresponds to an increase in accommodation. For ease of interpreting the magnitudes of effects, the ranges of the *y*-axes are the same as in Experiment 1.

Table 5
Mean (SD) of the dependent variables for the three difficulty levels, and results of statistical comparisons in Experiment 2 (df = 2,58 for ANOVA, df = 29 for paired t-tests).

	1. Easy Mean (SD)	2. Medium Mean (SD)	3. Hard Mean (SD)	ANOVA	1 vs. 2 t / Z	p	1 vs. 3 t / Z	p	2 vs. 3 t / Z	p
PDC (mm)	0.206 (0.200)	0.241 (0.157)	0.316 (0.197)	$F = 8.51, \boldsymbol{p} < \boldsymbol{.001}, \eta_p^2 = .23$	−1.37	.182	−4.11	**<.001**	−2.56	**.016**
PDC_{max} (mm)	0.580 (0.236)	0.632 (0.220)	0.671 (0.234)	$F = 4.76, \boldsymbol{p} = \boldsymbol{.012}, \eta_p^2 = .14$	−1.97	.058	−3.04	**.005**	−1.22	.232
PDC_{resp} (mm)	0.200 (0.220)	0.244 (0.171)	0.357 (0.220)	$F = 13.21, \boldsymbol{p} < \boldsymbol{.001}, \eta_p^2 = .31$	−1.55	.132	−5.05	**<.001**	−3.25	**.003**
RC (D)	−0.001 (0.132)	0.031 (0.112)	−0.034 (0.148)	$F = 4.49, \boldsymbol{p} = \boldsymbol{.015}, \eta_p^2 = .13$	−1.35	.187	1.88	.071	2.79	**.009**
VAC (deg)	−0.210 (0.464)	−0.356 (0.455)	−0.374 (0.590)	$F = 1.68, p = .195, \eta_p^2 = .05$	1.64	.113	1.46	.156	0.19	.849
RT (s)	6.489 (3.032)	6.826 (3.091)	10.771 (2.596)	$F = 55.6, \boldsymbol{p} < \boldsymbol{.001}, \eta_p^2 = .66$	−0.87	.390	−8.22	**<.001**	−9.03	**<.001**
CR (%)	93.3 (16.1)	74.4 (28.6)	50.0 (35.8)	$F = 28.6, \boldsymbol{p} < \boldsymbol{.001}, \eta_p^2 = .50$	3.35	**<.001**	4.28	**<.001**	3.04	**.002**

Note. A positive *PDC* means that the pupil dilated compared to the control slide. A negative *RC* means that the refraction became more negative (i.e., more accommodation) compared to the control slide. A negative *VAC* means that the vergence angle decreased compared to the control slide. The *t* / *Z* columns indicate the *t*-values from the *t*-tests and *Z*-values from the signed-rank test (the latter used for *CR* only). Statistically significant *p*-values are indicated in boldface.
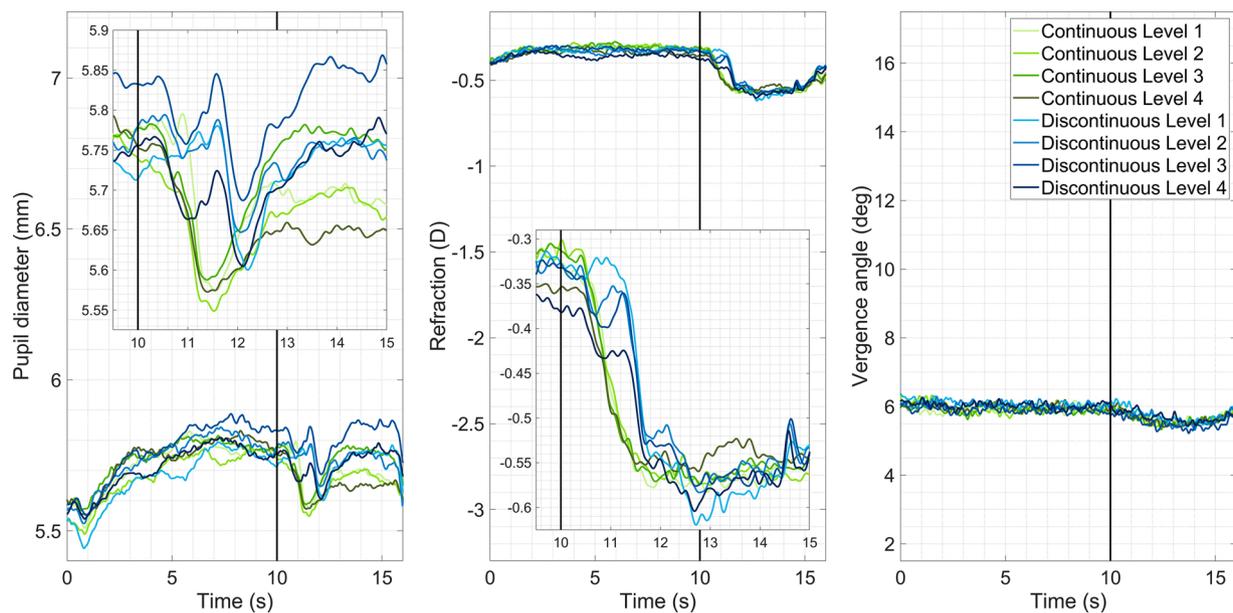
Fig. 7. Results for continuous and discontinuous movement of the ball in Task 2 of Experiment 2. Left: Mean pupil diameter. Middle: Mean refraction. Right: Mean vergence angle. The black vertical line positioned at 10 s indicates the transition from the control slide to the stimulus slide. A more negative refraction value corresponds to an increase in accommodation. For ease of interpreting the magnitudes of effects, the ranges of the *y*-axes are the same as in Experiment 1.

moved downwards. Participants' *VAC* was not significantly associated with depth cues (F(3, 87) = 0.12, p = .950, $\eta_p^2 < .01$) or movement type (F(1, 29) = 0.03, p = .863, $\eta_p^2 < .01$). No significant interaction was found between depth cues and movement type (F(3, 87) = 0.65, p = .587, $\eta_p^2 = .02$).

3.3. Discussion

Experiment 2 aimed to determine whether accommodation is a confounding factor in a pupillometry paradigm regarding mental demands (Task 1) and apparent depth (Task 2). Accordingly, we had participants perform multiplications (Task 1) and view pictorial stimuli with different monocular depth cues (Task 2) while measuring their pupil diameter, refraction, and vergence angle. As in Experiment 1, we used an outline font (Task 1) and line drawings (Task 2) to minimise interference from luminance changes. Because the screen was presented at only one distance, pupil responses due to luminance differences are unlikely.

In Task 1 of Experiment 2, participants' pupils dilated when performing a multiplication task, a finding consistent with Experiment 1. Again, the effects of the cognitive tasks on refraction and vergence were

small. The pupils of young adults constrict by about 0.25–0.4 mm/D of accommodation (Charman & Radhakrishnan, 2009; Kasthurirangan & Glasser, 2005; Schaeffel et al., 1993). Our measurements showed that the mean refraction change relative to baseline (*RC*) for the hardest multiplications was -0.034 D, based on which a pupil constriction of 0.01 mm would be expected. We observed a corresponding pupil dilation (*PDC*) of 0.316 mm, indicating that this dilation could not be caused by accommodation. Vergence angle changes (*VAC*) were small as well, being −0.4 deg at maximum.

In Task 2 of Experiment 2, the participants' pupils on average constricted up to about 0.2 mm, followed by re-dilation (see Fig. 7, left). The observed pattern is in line with Kasthurirangan and Glasser (2005), who, in a study where they measured pupil response and accommodation for various viewing distances, found that the pupils "started dilating while accommodation was still maintained" (p. 328). To investigate whether the observed pupil constriction is caused by a camera perspective distortion that occurs when rotating the eyes (Gagl, Hawelka, & Hutzler, 2011; Hayes & Petrov, 2016), we repeated the analysis of Task 2 for pupil height and width (see Fig. S2 in the Supplementary Material). The pupil height and width results were highly similar, suggesting that perspective distortion is not a cause of the observed pupil constriction. Instead, the pupil constriction corresponds to research showing that a

change in a visual stimulus (in our case: the appearance of monocular depth cues) and the onset of motion (in our case: a change in *y*-coordinate of the ball) cause pupil constriction, even if luminance is held constant (Barbur, Harlow, & Sahraie, 1992; Barbur, 1997; Li, Liang, & Sun, 2006). The pupil constriction can also be explained, in part, by accommodation: for a pupil diameter change of 0.25–0.4 mm/D, and a refraction shift of −0.2 D, a pupil diameter constriction of 0.05–0.08 mm would be expected.

In Task 2, we found that when looking at the ball's up-and-down movement, the measured refraction changed in the opposite direction than expected. If monocular depth cues influenced accommodation, one would expect the refraction value to become less negative, corresponding to an accommodation decrease, when the ball moved upward on the screen towards the depicted horizon. We measured refraction values that became more negative instead. This refraction shift may have been a genuine change in refraction but may also have been caused by a change in the participants' vertical viewing angle of about 5 deg while looking from the bottom of the screen upward towards the middle, causing a bias in the refraction measurement (see also Shapiro, Kelly, & Howland, 2005). Fig. S3 in the Supplementary Material shows the average vertical eye movement of all participants. It can be seen that eye-movements followed a smooth pattern for the continuous ball movement and a pattern resembling saccades and fixations for the discontinuous ball movement. The fact that the viewing angle strongly corresponds to the measured refraction is indicative of a bias in the refraction measurement caused by viewing angle.

Finally, in Task 2, there appeared to be a small effect of the level of monocular depth cues on refraction. While this effect should be replicated and unwanted interactions with eye movements should be ruled out, the effect is in line with the hypothesis that the illusion of depth can cause an accommodation shift (Koessler & Hill, 2019; Takeda et al., 1999).

4. General conclusions

This study aimed to examine to what extent accommodation is a confounder in pupillometry research. We had participants solve multiplication problems and view line drawings with different levels of monocular depth cues, while simultaneously measuring pupil diameter, refraction, and vergence angle using a photorefractor.

Pupil dilations while solving the multiplications were observed for different presentation distances, a finding that successfully replicates Hess and Polt (1964) and Kahneman and Beatty (1966). Many studies have shown that the pupils dilate while performing a cognitively demanding task (Ahern & Beatty, 1979; Marquart & De Winter, 2015; see Van der Wel & Van Steenbergen, 2018 for a review), but to the best of our knowledge, the findings of Hess and Polt (1964) and Kahneman and Beatty (1966) concerning pupil dilation at different presentation distances have not been replicated so far.

Vergence angle changes and refraction changes relative to baseline were small, except when the screen was presented close (20 cm) to the participants' eyes, in which case a refraction change of −0.24 D was observed. For the pictorial stimuli, apparent depth cues caused a refraction change in the direction consistent with real depth changes, but the effect was again small (−0.05 D for Level 4 depth cues compared to Level 1 depth cues). Because literature indicates that pupil sensitivity is about 0.25 to 0.4 mm/D, it is concluded that accommodation shifts are not a validity threat in pupillometry research.

4.1. Limitations

There are some caveats to be noted. First, this study presented effects at the group level. It is possible that for some persons, accommodation-induced pupil effects are, in fact, strong. A second limitation is that the experiments were conducted with young adults. Our samples consisted of engineering students, who can be expected to be proficient in mental

computation compared to other participant groups. Furthermore, it is well known that pupil diameter (Birren, Casperson, & Botwinick, 1950; Loewenfeld, 1979; Winn et al., 1994) and accommodative amplitude (Duane, 1922) decrease with age, which has consequences for the pupillary near reflex in terms of mm/D (Kasthurirangan & Glasser, 2006; Schaeffel et al., 1993). Furthermore, it may be the case that in extreme conditions, such as lengthy trials in combination with short viewing distances, participants have more difficulty to remain focused, which in turn could affect pupil diameter measurements, as noted by Janisse (1977, p. 12). Finally, we did not exclude myopic participants. We conducted correlational analyses between self-reported refractive error and the dependent variables of the two experiments (see Tables S1 and S2 in the Supplementary Material). The correlations were generally not strong enough to reach statistical significance.

Data availability

Photos from the experimental setups, image stimuli, video examples, raw data, and MATLAB code used for the analysis are accessible at https://doi.org/10.4121/13721038.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary Material

Supplementary material related to this article can be found, in the online version, at https://doi.org/10.1016/j.biopsycho.2021.108046.

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