Direct voluntary control of pupil constriction and dilation: Exploratory evidence from pupillometry, optometry, skin conductance, perception, and functional MRI

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ABSTRACT

We present a single case who can change pupil size on command with dilation of pupil diameter of around 0.8 mm, and constriction of around 2.4 mm. Using modern pupillometric and optometric techniques in combination with measuring electrodermal activity, various indirect mechanisms possibly mediating this phenomenon were tested: accommodation, brightness, increases in arousal by increased mental effort. None of these behavioral tests could support an indirect strategy as the mode of action, although it seems plausible that the case could have learned to gain control over the pupillary response by decoupling pupil size changes from accommodation and vergence in the near triad: Even at maximal accommodation, the case voluntarily constricted his pupil without changing vergence and could improve visual acuity by >6 diopters. Using task-based functional magnetic resonance imaging we found involvement of brain regions generating and mediating volitional impulses. Changes of the left pupil size were associated with increased activation of parts of the left dorsolateral prefrontal cortex, adjacent premotor areas, and supplementary motor area. It still remains open where these neural signals enter the final pathway, either innervating the pupil's dilator directly, or more indirectly by inhibiting the parasympathetically innervated antagonistic sphincter, and vice versa for constriction. To conclude, so far none of potential – conscious or unconscious – indirect strategies, may it be accommodative or vergence efforts or mental efforts and imaginations, could be observed or inferred to be fully responsible, suggesting direct voluntary control of pupil size in the present case.

1. Introduction

Direct control of the pupillary musculature is deemed impossible (Loewenfeld, 1993). However, many reports describe cases or larger samples that are presumably able to change their pupil size voluntarily (e.g., Table 13-1, p. 650; Loewenfeld, 1993). Loewenfeld (1993) concluded that these phenomena were due to the usage of indirect strategies: (…) an enhancement of the ability to bring about an indirect effect in a system that itself is involuntary and unconscious." (p. 650). From the various indirect strategies to elicit changes in pupil size, as described for example in Bumke (1911), Loewenfeld (1993), or Ekman et al. (2008) three distinguishable and mutually exclusive mechanisms can be delineated: **brightness-related**, including imaginations and shifts of attention, the **(self-)induction of physical or mental arousal**,

and **changes in the near triad**. In the present paper, we describe a case whose ability to substantially change pupil size in both directions cannot be accounted for (so far) by any of the previously described indirect mechanisms, challenging the common agreement in pupillometry literature. The present paper seeks to quantify the phenomenon, to investigate possible usage of indirect strategies and to provide ideas on putative mechanisms behind it.

A student of psychology at Ulm University, D.W., presented himself to one of the authors stating that he is able to change his pupils on command. The young man is 23 years old and presented without acute psychiatric or neurological disorder. A mild farsightedness was diagnosed at the age of 19 years which was confirmed by current optometric investigation. Binocular vision was without pathological findings, though, with a slight left-eye dominance. He reported that he had first

experienced his ability to change pupil size voluntarily at the age of around 16. It happened in the context of excessive computer gaming sessions at the end of which he tried to "relax" his eyes by rolling and performing voluntary saccades. Doing this once in the presence of a friend he found out that the size of his left pupil had changed and was smaller than the pupil of the right eye. D.W. then repeatedly tried to change pupil size in the absence of rolling maneuvers or saccades while trying to achieve a dissociation between convergence and accommodation, with the intention to produce diplopic images as feedback. At this time, he was unaware that he produced changes in pupil size in both directions, that is, larger and smaller pupil sizes. What he sensed were merely the perceptual consequences of changes in either direction, and as he describes, feeling the pupillary musculature while steering it directly. A detailed interview with D.W. can be found on OSF via htt ps://osf.io/7uf4x/). It was only until his first contact with a staff member of the Ulm psychological institute that he had received feedback about his ability to change pupil size from baseline in the direction of "smaller" and "larger". It is of special note that he could talk to the staff members with ease while changing his pupil (see Fig. 1; a video of this encounter with D.W. enlarging and constricting pupil size at direct prompt can be retrieved together with a second video recorded after our series of experiments via https://osf.io/7uf4x/).

During further exploration, the participant claimed not to use any other technique than feeling and activating the pupillary musculature directly. Specifically, he stated not to use the imagination of brightness or other stimulation, not to self induce emotional activation or mental effort, or to change the way he breathes or to change his muscular tone outside the eye.

Among the various cases claiming voluntary pupil control summarized by Bumke (1911) and Loewenfeld (1993), a case described by Bekhterev already in 1895 shows some similarities with our present case, which is why it is shortly reported here (Bechterew, 1895).

A 37-years old woman was able to voluntarily and repeatedly dilate her right pupil. Following Bekhterev's description, the patient had acknowledged some inflexibility of her right eye when focusing five years ago and had then noticed in a mirror a stark dilation of her right pupil, which had normalized after closing her eyes. This happened repeatedly in the context of effortful activities (e.g. writing, reading, stitching). Later she had noticed that independent from work she was in the position to dilate pupil size voluntarily by means of volitional efforts ("Willensanstrengungen"). On mere prompt she could dilate the right pupil (but not the left) repeatedly, with sizes two to three times larger than the left pupil. This state persisted until she initiated some blinks. Dilation was accompanied by weak sensations of pain over the right temple and nasal cavity; changes in body temperature or skin color were not noticeable.

Pupils constrict or dilate with increasing or decreasing illuminance, they constrict when looking to a closer object, accompanied by changes in accommodation and vergence during the near-response, and also scale with changes in arousal (Mathôt, 2018). These factors can be exploited for allowing indirect strategies to change pupil size. This was described in the literature by various authors, as summarized in the next sections. In the present case D.W., we aimed at testing whether he uses one of these indirect mechanisms when considering pupil size manipulation to be indeed voluntary in its strict sense (i.e., top-down controlled; immediate, on-command execution of behavior; Huestegge et al., 2019;

Hunter and Hudgins, 1934). Findings of the present study regarding on-command pupil size changes will be discussed in frameworks of voluntary control (i.e., Findlay and Walker, 1999; Huestegge et al., 2019) in the discussion. Building on the **link between changes in pupil size and illuminance**, anticipation and imagination of illuminance-conditioned stimuli may serve indirect dilation and constriction (Hunter and Hudgins, 1934). When thinking of bright or dark images, pupils slightly constrict or dilate, even when eyes are open and factual brightness is under external control and constant (Budge, 1855). Later, Goldflam (1922) presented results of a participant who lost eyesight in his teenage years. Being fully blind, this participant was able to alter pupil size by thinking of differentially bright images for constricting the pupil. The phenomenon was forgotten until Laeng and Sulutvedt (2014) were the first to show it in English literature, demonstrating that visually imagining pictures of the sun is associated with constricting pupils.

Already Bumke (1911) (for current reviews see also Einhäuser, 2017; Mathôt, 2018) suggested that **arousal** elicited by increased cognitive load dilates the pupil. Stoll et al. (2013) demonstrated that pupils can be intentionally dilated by opting to perform mental arithmetics as a mean to increase pupil-linked arousal. Similarly, self-induction of emotions using imagery can cause pupils to dilate via a link to arousal (Petrovic and Tschemolossow, 1931), as has been demonstrated repeatedly for the imagination of fearful situations (Ehlers et al., 2016; Ekman et al., 2008; Gratiolet, 1865). Other strategies affecting arousal are changes in bodily activity of all sorts (see e.g., Bumke, 1911; Ekman et al., 2008).

It was also reported that imagery can **shift accommodation**, by 'thinking near' vs. 'thinking far', and changes in pupil size may accompany this process (Malmstrom and Randle, 1976). Domrich (1849) reported that pupils constrict when thinking of a near object, and pupils dilate relative to that when thinking of a distant object, and Goldflam (1922) reported that the psychic momentum elicited by the impulse to converge alone is enough to let pupils constrict. Similarly, Sulutvedt et al. (2018) recently reported how pupil size changes due to shifts in the distance imagined. It is well known now for quite some time that accommodation can be controlled voluntarily (e.g., Marg, 1951; Sisson, 1937, 1938; Zentmayer, 1935; Provine and Enoch, 1975). An impressive example of trained near-accommodation in combination with pupil constriction was observed in children of the Moken people (Gislén et al., 2003; Gislén et al., 2006): For the acquisition of food, these children are regularly diving for shells without any additional equipment, and are reported to be able to accommodate strongly for improving underwater vision.

Accommodation during diving was associated with a substantial decrease in pupil size (Gislén et al., 2003), and later it was shown that this effect can be acquired also by European children (Gislén et al., 2006). Conversely, training of accommodation was reported to be more effective when pupil constriction was induced concurrently (Yuda et al., 2010).

Bechterew (1895) had tested and excluded most of these possibly subserving strategies to change pupil size in his patient. Based on then known physiology he had derived two possible mechanisms of action: Pupil dilation to be either mediated via inhibition of the antagonistic, parasympathetic pathway controlling the constriction of the pupil, or by sympathetically activating the dilating muscles. Consequently, he went through some different activating strategies like far accommodation, muscle tension, imagination of pain, fear or darkness, which, however,
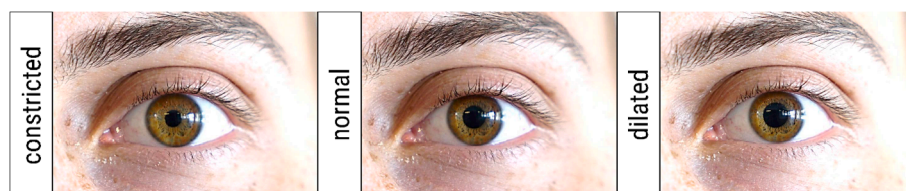

Fig. 1. Left eye at constant illuminance and fixation position. Left: voluntary constriction, center: baseline/normal pupil size, right: voluntary dilation.

he could dismiss. He finally concluded that only the ability to use voluntary, volitional effort to directly innervate the dilating, sympathetic nerves can explain the phenomenon, and assumed a preexisting connection between higher brain centers generating volitional impulses and centers that innervate the pupil dilating muscles ("(…) die Existenz einer vorgebildeten Verbindung der höheren, zu den Willensimpulsen in nächster Beziehung stehenden Hirncentren mit den die Pupillenerweiterer innervirenden Centren (…)." p. 491).

With present day neuroimaging techniques, we could test this precise prediction in our current participant. In a series of experiments, we further tested for possibly unknown usage of indirect strategies serving for pupillary constriction/dilation by our participant. We used video-based eye-tracking, skin conductance measurements, state of the art optometric testing, a visual acuity test at very near distances, and functional magnetic resonance imaging (fMRI) to quantify the phenomenon of pupil size changes, to exclude putative alternative sub-serving strategies, and to investigate its neural underpinnings. Therefore, different pupillometric experiments were developed where responses of the pupil were monitored during changes in brightness, during conditions with varying mental effort to induce changing levels of arousal, during a task where spots in different depths had to be fixated to account for effects of accommodation/vergence, and during a condition where he was instructed to voluntarily constrict and dilate the pupil. Between-conditions comparisons of pupil sizes were of main interest to test for indirect strategies. Electrodermal activity was assessed to track possible changes in arousal throughout all conditions. While electrodermal activity is not as closely correlated to mental effort as pupil size, increases in mental effort are associated with changes in skin conductance (Shimomura et al., 2008; Brouwer et al., 2014).

Visual acuity tests beyond the point of maximal accommodation without and with voluntary pupil constriction were obtained to exclude voluntary accommodation as sole cause for pupillary constriction.

Also, in order to test Bekhterev's prediction on the involvement of higher brain areas, the change-in-brightness experiment and the condition of voluntary changes in pupil size on command were implemented into task-based functional magnetic resonance imaging. The main outcome variable was estimated neural activation, particularly upon on-command changes in pupil size relative to the change-in-brightness conditions.

2. Expectations and research questions

2.1. Eyetracking/skin conductance

During pupillometric assessment, (1) effects of on-command dilation and constriction were to be quantified. The explorative comparison of relative effect sizes and signal dynamics, that is, velocity of changes, latencies of changes, inter- and intratrial variability, and size of changes for on-command changes with the most prominent factors affecting pupil size can help provide a first understanding of possible indirect strategies at use. As reference, the strongest factor, that is, (2) the pupil light response should be associated with the fastest, strongest and most consistent changes. (3) Changes during the near response should be associated with low variability, longer latency, and consistent, but less strong constrictions for fixating closer in comparison to the light response. Furthermore, (4) increases in mental effort should be characterized by relatively long latencies (due to more complex task processing and a longer latency) and should show comparably small but fairly consistent pupil dilations.

Were on-command changes due to the usage of an indirect auto-suggestive strategy (such as imagining differentially bright stimuli to produce a dilation/constriction or inducing mental effort, which could however only produce a dilation), then we would expect on-command changes in pupil size to be of relatively small magnitude in comparison to the light response, and to be characterized by relatively high inter- and intratrial variability and relatively long latencies.

For the concurrent skin conductance assessment, we expected skin conductance to covary with pupil size when mental effort is induced. Were the on-command changes be associated with a change in mental effort, then an increase in skin conductance for on-command dilation (but not constriction) should be observed.

Should on-command changes be a consequence of changes in vergence, then the tracked eye was to rotate inward for constriction and outward for dilation.

2.2. Optometric assessment

If on-command changes were a consequence of shifts in accommodation, then accommodation should change in opposite direction for dilation and constriction conditions, respectively.

2.3. Perceptual effects

On-command constriction cannot be solely caused by a shift in accommodation if, at the near point, where accommodation is maximal, a further constriction in pupil size could be achieved. If pupil size was then further constricted (and thus not solely driven by changes in accommodation), this should go in hand with better perceptual performance at and around the near point.

2.4. Functional MRI

Primary goal of the fMRI assessment was to test Bekhterev's prediction whether "higher brain centers generating volitional impulses" were involved during voluntary constriction and/or dilation. Therefore, two involuntary task conditions were designed akin to the pupil light response as outlined above with externally driven and experimentally controlled onset of brighter and darker illumination of the stimulation screen, and two conditions, in which the participant was asked to voluntarily change pupil size in each direction on command. Involvement particularly of dorsolateral parts of the frontal cortex was expected when contrasting the voluntary against the involuntary conditions. While the presence of such an effect would not necessarily rule out the use of indirect strategies, its absence would indicate the opposite, that is, a higher probability that any indirect and overlearned strategy was in action. If both voluntary conditions would show differential effects for the involvement of higher brain centers generating volitional impulses, this would indicate that one condition needed more volitional effort than the other, thereby supporting the functional existence of volitional impulses.

3. Material and methods

The experimental series and assessments were approved by the ethical board of Ulm University (number 20/20). Written informed consent was obtained before all investigations.

3.1. Pupillometric assessment

In the first experiment, effects of voluntary pupil control were set into relation with the three main conditions affecting pupil size: brightness, the near response, and changes in arousal. Electrodermal activity was measured as index of arousal. The participant took part in all experiments without his glasses. All experiments were performed monocularly for both eyes in the same way, in two sessions at different days. Here we focus on the data from the left eye, since results did not markedly differ between both eyes. Results for the right eye can be retrieved from the supplementary file accompanying this article and via https://osf.io/7uf4x/, along with horizontal gaze data for the left eye. As becomes evident from this data, shifts in gaze position could not have caused the presently reported results. It is also to note that there was some co-occurrence of changes visible from the non-investigated pupil

when our case dilated or constricted the investigated pupil on command.

3.1.1. Apparatus

An SMI Hi-Speed 1250 Eye tracker (SensoMotoricInstruments GmbH), running at 500 Hz, was employed, including a rest for chin and forehead. Blinks were interpolated using a version of the detection and filtering algorithm described by Georgi et al. (2014). Pupil sizes were normalized using a local baseline of 20 ms immediately foregoing each trial; average absolute pupil size at trial onset was 4.96 mm. Illuminance at eye-position was kept constant throughout the experiment, unless stated differently. The participant sat in a distance of 60 cm from the screen (27″, 1920 × 1080 px, 144 Hz) for testing effects of illuminance, arousal, and voluntary control. The experiments were implemented using 'PsychoPy 2' (Version1.90.1; Peirce, 2007). For testing the effects of the near response on pupil dilation, a wooden strip was fixed on top of the eye tracker. From this strip, black wooden pearls were hanging down at 30 cm, 60 cm, and 90 cm of distance to the eyes of the participant in a line, at the same coordinates as the screen center was before. Data were acquired monocularly, that is, one eye was covered by thick gaze and adhesives. It is of note though, that the participant was able to dilate and constrict pupils on command also binocularly.

Electrodermal activity was assessed using a NeXus-10 Mark II (Mind Media BV) device running at a sample rate of 32 Hz using Ag/AgCl electrodes. Electrodes were attached to the tips of index and middle fingers of the left hand. Higher arousal is associated with higher skin conductance and therefore an increase in electrodermal activation (for more details see Boucsein, 2012).

3.1.2. Procedure

Conditions were presented in a blockwise manner. To start a trial, the participant needed to look at the center of a gray circle of 7.34° visual angle in diameter. Within this circle, a fixation cross was presented in black. For a valid trial, gaze position had to be kept constant within the circle for 5 s. Following these 5 s, edge lines of the circle turned green as feedback that the trial has been absolved correctly for 4 s. The inter-trial interval (ITI) was three seconds long, during which at an intermediate gray, the circle and the fixation cross were presented.

3.1.3. Brightness

Effects of changing illuminance on pupil dilation were investigated in an ABBA sequence, with ten single trials for increasing screen brightness and ten trials for lowering screen brightness. At baseline level, screen brightness was constant at 83.3 cd/m^2 (gray), lower screen brightness was constant at 0.4 cd/m^2 (black), and higher screen brightness was constant at 265 cd/m^2 (white). Brightness changes from baseline were instantaneously.

3.1.4. Arousal/mental effort

To test for arousal as potential indirect mechanism we used induction of mental effort because it constitutes the arguably best investigated possibility. Note however, that possible changes in arousal throughout all conditions were also tracked by continuously assessed electrodermal activity. To test on effects of mental effort, the participant was presented with 10 multiplication tasks including a one digit and a two-digit number as factors written in black letters in the center of the gray circle (e.g., '17 × 3'). Numbers ending with 0, 1, or 5 were excluded. When a trial was aborted, a new task was determined by chance for the following trial. Upon trial completion, the participant was asked to report the result of the calculation orally to the two experimenters present in the laboratory to ensure compliance with the task. The timing of events in a trial with a 4 s response interval and an ITI of 3 s ensured that effects of pupil size were not affected by the verbal response (e.g., Brych et al., 2021).

3.1.5. Near response

Investigating the near response, the monitor was put aside and the participant was instructed to fixate a pearl hanging down from a wooden strip at a distance of 60 cm. Upon instruction of one of the experimenters, he needed to fixate either the farther (90 cm) or the nearer pearl (30 cm) in ABBA sequence. Upon trial completion, the participant was instructed to fixate the intermediate pearl at 60 cm again, from which baseline was taken for the next trial.

3.1.6. Voluntary changes

For voluntary changes in pupil size, the participant was presented with either '<' or '>' in the center of the gray circle as symbols to constrict or dilate pupils, respectively, until the green circle fed back trial completion. Again, ten trials were obtained, presented in ABBA sequence.

Data and supplementary information are available via https://osf.io/7uf4x/.

3.2. Optometric assessment

Optometric assessments were performed by a studied optician using the ZEISS i.Profiler and subjective testing for validation.

3.3. Perceptual effects of voluntary pupil constriction

To further test whether voluntary pupil constriction is potentially solely driven by changes in accommodation, we applied a visual acuity test for fine grained stimuli in near distance. Both, accommodation and pupil size affect image resolution. However, presenting stimuli beyond the range of accommodation could allow for measuring the effects of voluntary pupil size changes on visual acuity. The range of accommodation is usually defined between far and near point. At the near point, maximal accommodation still results in a sufficiently sharp image. This implies that fine grained stimuli closer than the near point cannot be resolved sufficiently anymore. Hence, by additionally voluntarily constricting pupil size, the near point should become closer to the participant's eye than without changing pupil size at will.

To derive the near point we presented fine grained u-shaped stimuli with four possible opening directions (up, down, right, left) of retinally constant size in six successively closer distances (27.1 cm, 22.5 cm, 18.0 cm, 13.5 cm, 9 cm, 4.5 cm) on a Motorola Z3 play smartphone (2160 × 1080 pixels at 6 in. screen diagonal) that was mounted in front of the participant's left eye. The precise distances were derived based on the technical limitations of the screen, that is at closest distance, stimuli had a size of 3-by-3 pixels, and of 8-by-8 pixels at the farthest distance from the eye. Stimuli were gray on a black background. The room was very dimly lit, illuminance as measured at eye position was at 0.05 lx throughout all distance conditions. The 62.5% correct detection threshold of a fitted psychometric function was defined as the near point. The same experiment was conducted twice, first with the instruction to orally give the direction of the opening of the u-shapes, second with the same instruction and the additional instruction to constrict pupil dilation voluntarily when trying to identify the direction.

3.4. Functional MRI

Only the participant's left eye was studied. Therefore, before entering the MR scanner, his right eye was covered.

3.4.1. Functional challenge

The brightness conditions (involuntary changes in pupil size) and the active constriction/dilation task (voluntary changes in pupil size) as described above were combined into one functional MRI session lasting 13.4 min. Thus, there were four task conditions. Per each condition 20 trials were measured. For the remainder of the text these four conditions are termed: BRIGHT and DARK, referring to trials to induce involuntary changes in pupil size by experimentally manipulating the brightness of the visual background during fMRI; CONSTRICT and DILATE denote

trials where the participant was asked to voluntarily change pupil size. The trial structure was similar for all conditions: One single trial lasted 6 s. During the first 4 s, a gray circle (RGB code: (166,166,166)); with black line color and with size of 3.4° visual angle was presented in the center of the screen. The screen's background was white in the BRIGHT condition, black in the DARK condition, and gray (RGB code: (145,145,145)) during CONSTRICT and DILATE. Depending on the condition, a black character was shown within the circle: During BRIGHT and DARK, a fixation cross was presented. In the conditions CONSTRICT and DILATE, '<' or '>' informed the participant to constrict or dilate his left pupil, respectively. During the last 2 s of each trial, the character within the circle was replaced by the fixation cross, and the line color of the circle turned green to feed back trial completion. Of note, given the participant's high compliance and interest, and to avoid contamination of brain activation by hand/finger-related motor processing, we deliberately did not require him to press a button to confirm his attention during the fMRI session similar to the pupillometric experiments. Trials were separated from each other by inter-trial intervals (ITI) of varying length ($M = 3.4$ s, range: 1.9 s to 8.4 s). During ITI, a gray circle (RGB code: (166,166,166)) with black line color containing a fixation cross was shown on gray background (RGB code: (145, 145,145)). After the first half of the experiment, a message on screen announced a short break of 35 s during which acquisition of functional images was not interrupted.

The program 'Optseq2' (http://surfer.nmr.mgh.harvard.edu/optseq/; see also Dale, 1999) was used to obtain a trial sequence permitting efficient estimation of the hemodynamic responses associated with each condition. Trial order and trial onsets, as initially delivered by the program, were modified such that a specific condition did not appear more than twice in direct succession. Furthermore, onsets were jittered by randomly adding fractions of the fMRI repetition time (TR). 'Presentation' (Version 18.1, Neurobehavioral Systems Inc., San Francisco, USA) was used for stimulus presentation on a 32″ LCD display (NordicNeuroLab AS, Bergen, Norway) at 1280 × 720 pixels resolution, projected to participants' eyes by a mirror. All light sources in the MR cabin, except for the LCD display, were completely dimmed. In the run-up to the experiment, the gray levels reported above had been selected such that the specific screen brightness associated with each task condition closely corresponded to the experimental setup reported above (lower screen brightness: 1.2 cd/m^2; baseline screen brightness: 85 cd/m^2; higher screen brightness: 242 cd/m^2).

3.4.2. MRI data acquisition

MRI was performed on a 3 Tesla MAGNETOM Prisma with a 64 channel head/neck coil (Siemens AG, Erlangen, Germany). Functional images measuring the T2*-weighted BOLD signal were obtained using an echo-planar pulse sequence (EPI) with TR = 2000 ms, echo time (TE) = 33 ms, flip angle = 90°, bandwidth = 2136 Hz/px, PAT factor = 2 (GRAPPA mode), field of view (FOV) = 220 mm, matrix size = 90 × 90, ascending slice acquisition yielding 32 transversal slices, slice thickness = 3.0 mm, interslice gap = 1.0 mm, voxel size = 2.44 mm × 2.44 mm × 4.00 mm. Scan time was 13.7 min, corresponding to 411 EPI volumes. A structural T1-weighted image was acquired using a magnetization prepared rapid acquisition gradient echo sequence with following parameters: TR = 2300 ms, TE = 2.98 ms, inversion time = 900 ms, flip angle = 9°, bandwidth = 240 Hz / px, PAT factor = 2 (GRAPPA mode), FOV = 256 mm, matrix size = 256 × 256, voxel volume = 1 mm^3, slice orientation: sagittal; scan time: 5.5 min.

3.4.3. Image preprocessing and analysis

Preprocessing and statistical analyses of MRI data were performed using 'Statistical Parametric Mapping' (SPM Version 12, Wellcome Department of Cognitive Neurology, London, UK). Functional EPI images were slice time corrected (reference slice: 16) and spatially realigned to the mean EPI. After coregistering the T1 image to the mean EPI, the T1 image was segmented using SPM's 'normalize' routine, and the

resulting deformation field was applied to all preprocessed images. The normalized EPI images, having a voxel size of 2 mm × 2 mm × 2 mm, were smoothed using a Gaussian kernel with 6 mm full width at half maximum. Normalization and smoothing were applied to obtain coordinates in Montreal Neurological Institute (MNI) space (for comparability) and to facilitate statistical inference which is based on random field theory requiring a certain degree of smoothness.

To estimate task-related brain activation, preprocessed fMRI data were modelled using a General Linear Model. Separate regressors were formed for BRIGHT, DARK, CONSTRICT, and DILATE on the basis of their respective trial onsets, and a trial duration of 4 s. Two further regressors modelled the remaining 2 s of all trials (i.e., feedback circle) collectively, and the ITI periods (variable duration), respectively. Resulting boxcar functions were convolved with the canonical hemodynamic response function. The spatial realignment parameters were also added to the design matrix. To remove low-frequency scanner drifts, data were high-pass filtered (cutoff: 128 s). An autoregression model of polynomial order 1 was used to account for temporally correlated residual errors.

After model estimation, we first tested for significant, conjoint brain activation across all four task conditions in order to infer that the visual task had elicited neural activation in brain regions known to play a role in visual processing, thereby validating the fMRI task and subject's compliance. It is of note in this context that the explicitly modelled baseline conditions (the ITI and the green circle indicating the end of the trial) were not taken into account during contrast formulation for these main effects, as both control conditions are visual in nature and may mask out neural activation of primary visual areas. Neural activation of all main effects were calculated beyond and above the explicitly modelled baseline conditions inherent in the design matrix, but were not directly contrasted with those conditions. The statistical parametric map was inspected using an uncorrected voxel-height threshold of $p < 0.05$, with a cluster-extent threshold of 231 continuously significant voxels to show clusters significant at a level of $p < 0.05$, uncorrected.

Next, we examined whether there were neural correlates specific to voluntary pupil constriction and dilation relative to changes in brightness. Accordingly, the average of both voluntary conditions was compared against the average of both involuntary conditions using a directed one-tailed t-contrast. To allow for a meaningful interpretation, the resulting statistical parametric map was inclusively masked ($p < 0.05$) by two further contrasts, testing for constriction-related neural activation ('CONSTRICT'), and for dilation-related neural activation ('DILATE'). Again, these two contrasts were computed beyond and above the explicitly modelled baseline conditions which, however, did not enter contrast formulation. The threshold applied to the statistical parametric map was set at $p < 0.05$ and a cluster extent threshold of 231 voxels.

Finally, we compared both voluntary conditions against each other using two one-tailed t-contrasts ('DILATE > CONSTRICT', 'CONSTRICT > DILATE') at the level of $p < 0.05$, uncorrected at the voxel level and with an extent threshold of 20 contiguously significant voxels. Statistical testing was confined to a binary mask encompassing significant clusters from the previous analysis step.

4. Results

Throughout all experiments, experimenters were in the room and discerned not even slight overt changes in behavior while the participant changed his pupil size actively compared to the normal viewing conditions.

4.1. Pupillometric data

Average pupil courses are visualized in Fig. 2 (left) in conjunction with all individual signal courses for the left pupil (Fig. 2 center and right).
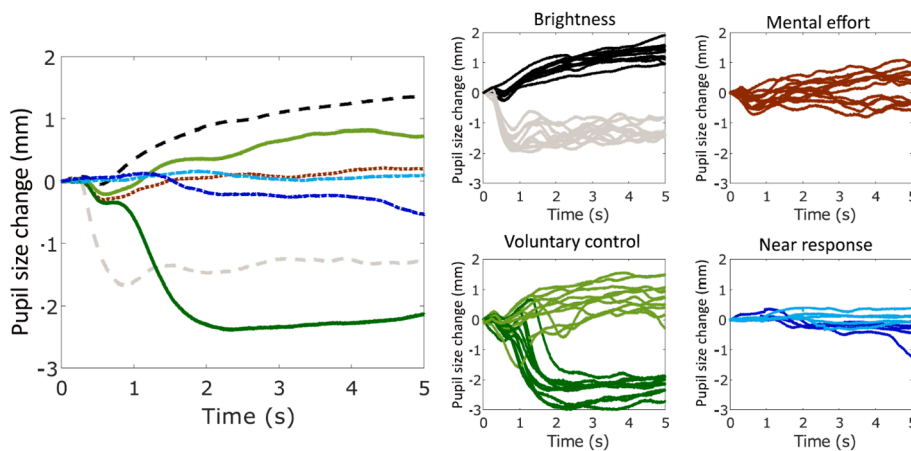
Fig. 2. Left: Average pupil size relative to the local baseline over time for increasing brightness (gray, dashed), decreasing brightness (black, dashed), mental effort (brown), voluntary dilation (light green, solid), voluntary constriction (dark green, solid), and fixating to 30 cm (dark blue, dashed/dotted), as well as fixating to 90 cm (light blue, dashed/dotted). Right: pupil size changes in all individual trials in the respective conditions relative to baseline. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For brightness, the pupil constricted instantaneously with increased screen brightness and dilated with lowering screen brightness in all trials. Pupil dilation followed the typical response pattern observed in the light response (e.g., Mathôt, 2018); a stronger constriction at shorter latency for increased brightness compared to decreased brightness. Constriction amounted to about −1.5 mm and dilation to about 1.3 mm relative to the foregoing baseline on average. Pupil responses to brightness were generally very consistent and characterized by the lowest inter-trial variability among the investigated factors.

For arousal, the calculation of arithmetic tasks presented on screen was, as expected, associated with a slight increase in pupil dilation of about 0.2 mm at the maximum of the average signal curve. In comparison to effects of screen brightness, there was considerably more inter-trial variability for effects of arousal; not all responses were characterized by an absolute increase in pupil dilation.

For the near response, pupils changed for about −0.55 mm at the minimum relative to the baseline, while pupils dilated slightly up to about 0.13 mm at the maximum for fixating the more distant pearl. As for mental effort, near response trials were characterized by higher inter-trial variability than pupil responses for brightness or on command. Other than for the light reflex, the decrease in pupil dilation when fixating at a closer object became gradually larger over time.

For voluntary constriction, an average constriction of −2.4 mm was achieved relative to baseline. Interestingly, signal courses of voluntary constriction show striking concordance with the change elicited by the light response, i.e., a steep initial dip in pupil size, followed by relatively constant smaller pupils over time. However, on average the onset of this shift occurs somewhat later and individual trials showed more variance in the onsets of constrictions compared to the light response. This initial dip can be explained by the visual response to the cue and its interpretation, which necessarily entails a lagged response relative to the reflexive response. For voluntary dilation, a dilation of about 0.8 mm was observed. While voluntary dilation was less consistent compared to voluntary constriction in its pattern, the participant clearly enlarged his pupil in all trials. Again, voluntary dilation showed a comparable signal dynamic as for the light response to lower illuminance.

Concurrent assessment of skin conductance showed no substantial changes in electrodermal activity in any of the conditions above (see Fig. 3). Descriptively, higher skin conductance was associated with the constriction rather than with the dilation condition. For mental effort, skin conductance shows a slight increase after 2.5–3 s. Taking into account initial task processing as well as the response latency of the electrodermal activity, this suggests a slight increase of sympathetic arousal on average. Skin conductance, however, generally showed no specific pattern on an individual trial basis.
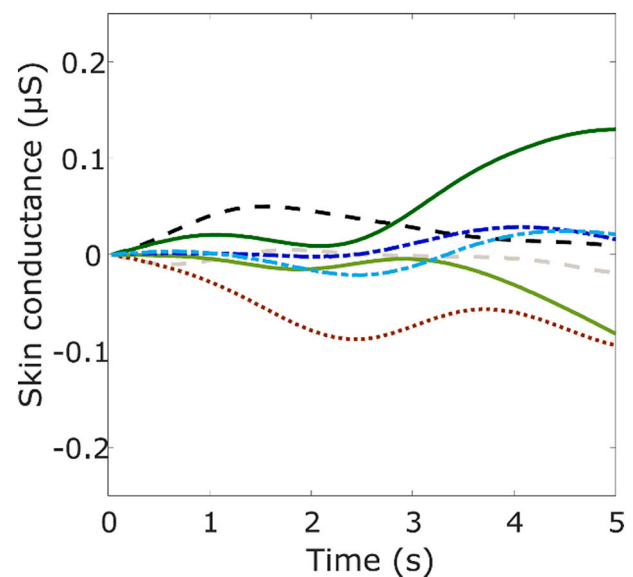

Fig. 3. Average change in skin conductance relative to the local baseline over time for increasing brightness (gray, dashed), decreasing brightness (black, dashed), mental effort (brown), voluntary dilation (light green, solid), voluntary constriction (dark green, solid), and fixating to 30 cm (dark blue, dashed/dotted), as well as fixating to 90 cm (light blue, dashed/dotted). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.2. Optometric assessment

During optometric assessment, spherical and cylinder power were measured for 'regular' pupil size, as well as during voluntary constriction and dilation for the left eye. Relative to regular pupil size (+0.75 dpt), a substantially different spherical power was observed during voluntary constriction (−7.00 dpt), whereas no considerable different spherical power was observed during voluntary dilation (+1.00 dpt).

4.3. Perceptual effects of voluntary pupil constriction

Recognition performances and psychometric functions with regular and voluntarily constricted pupil are visualized in Fig. 4. While recognition performance was fairly similar at 3.7 dpt, 4.4 dpt and 5.6 dpt of distance for both experiments, recognition performances differed at 7.4 dpt with descriptively better performance for the constricted pupil than for the normal viewing condition ($t(30) = 0.13$, n.s.), and statistically significant better performance for the constricted pupil than for the
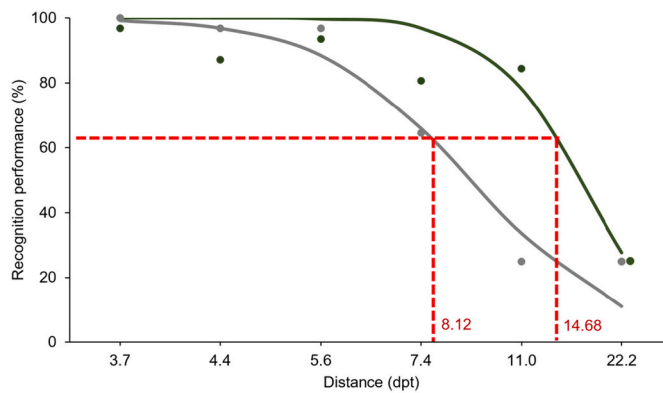
Fig. 4. Recognition performances for the visual acuity tests performed in near distances together with fitted psychometric functions. Gray denotes the normal viewing condition, dark green the voluntary constriction condition. The horizontal red line depicts the 62.5% correct detection threshold (near point). Vertical lines indicate the near point at 8.12 dpt for the normal, and at 4.68 dpt for the voluntary constriction condition. Note: The x-axis shows distances in diopters, i.e., distance to the eye decreases from left to right. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

normal pupil at 11.0 dpt ($t(30) < 0.001$). The near point at the 62.5% correct detection threshold of the fitted psychometric functions on recognition performances was at 8.12 dpt for the acuity tests performed with regular ($R^2 = 0.94$) and at 14.68 dpt with voluntarily constricted pupil size ($R^2 = 0.96$). This demonstrates that the participant could move his near point closer to the eye by 6.56 dpt when constricting his pupil size voluntarily at maximal accommodation.

4.4. Functional MRI data

Table 1 summarizes all brain activation results, and relevant between-condition differences thereof. All task conditions in conjunction significantly activated the bilateral inferior occipital gyri (Table 1A). Contrasting neural activation associated with voluntary against involuntary changes in pupil size, this analysis revealed effects in occipital and parietal brain regions (Table 1B). Frontally, both voluntary conditions led to significant activation in motor, pre-motor areas, including the supplementary motor area, and of aspects of the dorsolateral prefrontal cortex, particularly the left inferior frontal gyrus (around Brodmann area 46/9). Comparing both voluntary conditions against each other within the resultant statistical parametric map from the computation above (Table 1B), during pupil constriction relative to pupil dilation, significantly greater activation was detected in three primarily left-sided clusters comprising parts of the inferior and middle occipital gyrus, and the lingual gyrus (Table 1C). Greater brain activation for pupil dilation compared to pupil constriction was evident in the left inferior frontal gyrus and in the supplementary motor area (Table 1D, and Fig. 5).

5. Discussion

In this study, we present evidence from a case that challenges the broad agreement among pupillometric researchers that voluntary changes in pupil size cannot be induced directly by mere volitional effort. So far, in a number of experiments, we have tested possible indirect strategies subserving changes in pupil size. Quantitative pupillometry revealed that D.W. was able to constrict his pupil on command to the extent of −2.4 mm, and to dilate his pupil on command to the extent of +0.8 mm (both measures relative to baseline). Pupillometric assessments demonstrated relatively mild effects of accommodation on pupil size as induced by the distances of 30 cm and 90 cm relative to 60 cm.

Table 1

Brain regions obtained for different conjunctions of individual contrasts (the sign "∩" indicates conjunction). **A)** and **B)** Statistical thresholding was performed at an uncorrected threshold of $p < 0.05$ (voxel level), and a cluster extent threshold of k = 231 voxels (cluster-level: $p < 0.05$, uncorrected). Level of significance in **C** and **D**: $p < 0.05$ and k = 20 voxels.
L: left; R: right.

	Brain region	Number of voxels	Peak voxel (MNI space)			
			x	y	z	z-Score
A) BRIGHT ∩ DARK ∩ CONSTRICT ∩ DILATE						
R	Inferior occipital gyrus	494	32	−92	−2	5.36
L	Inferior occipital gyrus	479	−32	−90	−8	5.17
B) Voluntary > Involuntary ∩ CONSTRICT ∩ DILATE						
L	Middle occipital gyrus	3759	−28	−90	0	7.03
L	Inferior occipital gyrus		−26	−92	−8	5.45
L	Lingual gyrus		−22	−64	−8	4.47
R	Lingual gyrus	1915	22	−88	−8	4.93
R	Middle occipital gyrus		40	−74	4	4.68
R	Inferior occipital gyrus		32	−86	−6	4.55
R	Superior occipital gyrus	503	26	−64	30	4.22
R	Superior occipital gyrus		26	−76	36	2.75
L	Supplementary motor area	436	−4	16	54	3.49
L	Supplementary motor area		−10	0	58	3.02
R	Precentral gyrus	654	52	0	50	3.42
R	Postcentral gyrus		54	−16	48	3.25
L	Precentral gyrus	390	−46	2	40	3.18
L	Precentral gyrus		−38	−6	56	2.81
L	Postcentral gyrus	603	−48	−28	56	3.14
L	Inferior parietal lobule		−44	−50	58	2.91
R	Superior parietal lobule	472	22	−60	60	3.02
R	Inferior parietal lobule		42	−42	54	2.71
L	Inferior frontal gyrus	288	−42	34	22	2.87
L	Inferior frontal gyrus		−40	16	28	2.29
C) CONSTRICT > DILATE, masked by B)						
L	Lingual gyrus	80	−22	−70	−4	2.96
L	Inferior occipital gyrus	70	−14	−100	−6	2.81
L	Middle occipital gyrus	22	−22	−94	10	1.91
D) DILATE > CONSTRICT, masked by B)						
L	Inferior frontal gyrus	62	−38	32	22	2.69
L	Supplementary motor area	23	−8	−2	56	2.48

While **accommodation** could in principle account to some extent for constrictions, particularly sudden, stark dilations should not be producible this way (e.g., Kasthurirangan and Glasser, 2005). Combining eye-tracking results with optometric testing demonstrated that voluntary constriction was associated with a change in accommodation, whereas voluntary dilation was not, or only very mildly associated with a change in accommodation, which is in line with assumptions on the effects of the near response. Additionally, we could demonstrate that the near point could be shifted closer to the active eye at maximal accommodation when D.W. was voluntarily constricting his pupil. Such an increase in visual acuity can be explained only by activating the pupillary musculature, because accommodation should be maxed out at the near point. Furthermore, D.W. could also change pupil sizes with both eyes open without considerable changes in vergence. For the monocularly tested eyes, no substantial inward/outward rotation of the eyes could be found during voluntary changes relative to the other conditions (see https://osf.io/7uf4x/).

Self-induction of **arousal** can also very likely be ruled out to account for the dilations since mental effort had a substantially smaller effect on enlarging pupil size than changes in illuminance and voluntary dilation, which was further characterized by a differential signal dynamic. While effects of mental effort on pupil size, at around +0.2 mm dilation relative to baseline towards the end of trials, on average appear small, they are in fact only small in comparison with the other factors investigated here. In one of the most influential manuscripts on that matter,
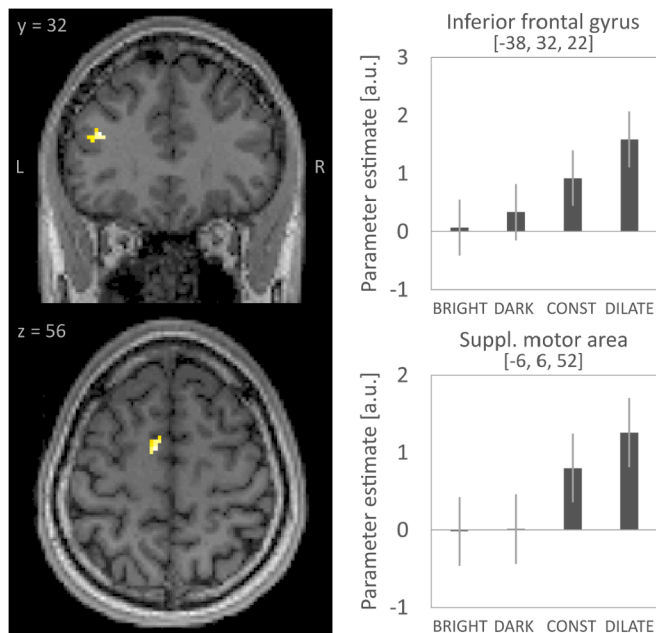
Fig. 5. Left: Brain slices of D.W.'s individual T1 image after normalization into standardized stereotactic space (MNI). The upper slice shows voxels located in the left inferior frontal gyrus bearing significantly greater neural activation during voluntary dilation relative to voluntary constriction of pupil size ($p <$ 0.05, k = 20 voxels; see also Table 1D). The lower slice depicts voxels significant in the same contrast representing the supplementary motor area. Right: Estimated neural activation for each of the four conditions derived from corresponding peak voxels. Error bars denote standard error of the mean. Abbreviations: a.u.: arbitrary unit; L: left; R: right; CONST: voluntary constriction; Suppl.: Supplementary.

Kahneman and Beatty (1966) report effects in the range of effects reported here for retaining up to 6 digits in working memory. Only 7 digits elicited a stronger maximal increase of about 0.5 mm relative to baseline. To produce dilations of 0.8 mm and beyond, as D.W. could, load must be massive, if it was possible at all. Furthermore, D.W. could talk to the investigators at ease while changing his pupil sizes in either direction. If, however, he was employing some self-induction of load, it is hardly conceivable that the same would not have affected the simultaneously ongoing conversation (see https://osf.io/7uf4x/ for such a video). Skin conductance data, where constriction but not dilation on command was associated with slight increases, suggests no involvement of arousal. Together, these results render any indirect strategy employing the link between arousal and pupil dilation rather unlikely.

In summary, none of the presently investigated indirect strategies for changing pupil dilation can account for the observed effects. Of course, it is impossible to test for all potential indirect strategies. On the other hand, no strategies are known to the authors that would not align with the three mechanisms of arousal, brightness, and accommodation/vergence. On top of the notable effect sizes for both dilation and constriction, latencies and slopes of the observed changes also argue for direct muscular involvement: First, imagination related strategies would require more time to produce effects, although training might allow to induce changes less slowly (Ehlers et al., 2018); second, indirectly mediated effects were generally substantially smaller in size, e.g., Sulutvedt et al. (2018) show the maximum averaged differences in pupil dilation between imagining distant vs. near objects to amount to about 0.05 mm, that is, about 70 times smaller than for the described case here. Ekman et al. (2008) let their participants increase and decrease their pupil size alternatingly in direct succession and give effect sizes in percentage change relative to the foregoing dilation/constriction condition. Participants on average managed to enlarge their pupils by about 10%. At the same time, participants were, on average, only able to revert

this movement during the constriction condition. During 10 s relative to the foregoing dilation conditions, pupils maximally constricted by 29.6% using shifts in focus as strategy. For dilation, a change of 28.2% was achieved at maximum relative to the foregoing constriction using physical activity (Ekman et al., 2008). Relative to the average pupil dilation of the last second of voluntary dilation, D.W. managed to constrict his pupil by 54.3% during 5 s; similarly, relative to the average last second of the foregoing constriction, D.W. managed to enlarge his pupil by 104.1%. Third, no investigation is known to the authors that showed similar slopes, especially when it comes to constricting pupil size on command from a resting baseline. Together, these findings speak in favour of a direct control of the pupillary musculature.

Interestingly, already 125 years ago Bekhterev had been going through a list of possible indirect strategies (imagination of differential brightness or darkness, muscle tension, self-induced arousal (by pain or fear), far response, increased vasomotor tone), but could not find strong enough evidence for any of them. He finally concluded that the phenomenon cannot be explained without the assumption to actively involve the sympathetic pathway motivating his then visionary prediction that there must exist a connection between brain areas that process volitional impulses and those brain regions that innervate the muscle for pupil dilation.

Present functional magnetic resonance imaging could confirm a major part of this prediction. Particularly for pupil dilation, involvement of aspects of the dorsolateral prefrontal cortex (Brodmann area 46/9), and the supplementary motor area were observed which most likely represent the brain regions generating (e.g., Abe and Hanakawa, 2009; Goldman-Rakic, 1987; Grafton and Volz, 2019; Hanakawa, 2011) and mediating (e.g., Haggard, 2008; Miller et al., 2018) the volitional impulses that finally lead to pupil dilation. However, where these volitional impulses impinge on the anatomical circuits controlling pupil size could not be observed.

Constriction and dilation of the pupil are controlled by a balanced interaction of parasympathetic and sympathetic components. For example, dilation may result from either direct sympathetic activation of the dilator muscles, or by inhibition of the parasympathetically controlled activation of the pupil's sphincter for which the midbrain's Edinger-Westphal nucleus is a significant relay (Loewenfeld, 1993). From studies in experimental animals (Joshi et al., 2016) and pharmacological treatments in humans (Steinhauer et al., 2004) it has been suggested that dilation is mediated by activation of the noradrenergic locus coeruleus which may exert inhibitory influences on the Edinger-Westphal nucleus, thereby reducing the parasympathetic tone of the pupil's sphincter. This pathway has even been suggested to be the primary mode of action when pupils dilate in response to emotional arousal or mental effort (Mathôt, 2018). However, this explanation would make it necessary that the connection between the locus coeruleus and the Edinger-Westphal nucleus is direct and indeed inhibitory which is not certainly known, particularly in humans. Secondly, results supporting this pathway usually stem from studies that had experimentally modulated levels of arousal and/or mental effort. However, these modulations were entirely absent in the present voluntary condition, and electrodermal activity as an index of arousal in one of the control experiments with varying mental effort was also not related with dilation.

Arousal and its effects on the noradrenergic locus coeruleus system are also less likely from another perspective: Our case already has a longer learning history of changing pupil size voluntarily. Thus, another aspect of neuroplasticity arises to account for the present phenomenon, that is, forming new and specific synapses along the efferent route of the oculomotor nerve. As one possible candidate region for this to happen, the ciliary ganglion is suggestive since it is where the parasympathetic and sympathetic branches are in closest neighborhood to each other. While the sympathetic nerves go directly through the ciliary ganglion, the parasympathetic nerves synapse there onto the short ciliary nerves innervating the sphincter. One possibility therefore suggests that our case had formed synapses in the ciliary ganglion to inhibit the

antagonistic sphincter, leading to dilation. This assumption receives some initial support from our participant's self-report that during acquisition of voluntary changes in pupil size he was initially not aware of the fact that he could do this in both directions, i.e., constriction and dilation. Absence of awareness may indicate a less direct route and also supports the suggestion that during initial acquisition and ensuing practicing new synapses had been to form. However, we want to stress here that the above discussed hypothesis is not more than a speculation for which we cannot present any supporting data.

While frontal cortical correlates for dilation (in comparison to constriction) emerged from the functional data, the inverted contrast direction (constriction > dilation) did not directly reveal another indication of specific frontal neural activation associated with constriction. The conjunction analyses of all four conditions of interest made it evident from the strong visual area activation that the participant was adhering to task instructions. Also, the estimated parameter of the voluntary constriction condition (Fig. 5) did indeed show substantial neural activation engaging the dorsolateral prefrontal cortex and motor areas, but to a lower degree than that for voluntary dilation. This relatively lower magnitude of neural activation may indicate that constriction was less difficult than dilation because the neural circuit for the pupil reflex is embedded in the neural circuit for accommodation (Mathôt, 2018; Fig. 3a), and accommodation is associated with constriction. In other words, the volitional impulses for constriction exist the same way, reach the efferent part of the oculomotor nerve downstream the supplementary motor area and may either directly innervate the sphincter, or indirectly inhibit the antagonistic dilator, consequently leading to constriction. Again, the exact mechanism remains unclear and with it, where this happens.

Existing theoretical frameworks on levels of control in oculomotor behavior, so far essentially on saccades, describe different levels of control, ranging from bottom-up driven, automatic, over highly learned, automatized, to top-down driven, voluntary controlled action (e.g., Findlay and Walker, 1999; Huestegge et al., 2019). Pupil responses can be discussed in this framework as well: The pupillary light response is a clear example for an automatically controlled pupil movement. Various indirect strategies point to the principal possibility to learn and automatize, but not to the extent of voluntary control of the pupillary response. Our case, given the present data, most likely qualifies for top-down driven voluntary controlled direct action. This further poses questions regarding the kinds of eye movements which can become parts of a system under a voluntary regimen. Besides fixations (and thus, also saccades) and pupillary movements, one might also think about smooth pursuit, vergence movements, or microsaccades. These issues also put forward questions concerning the interaction between central and autonomous nervous pathways. Future studies should be designed to provide answers to these questions.

Taken together, the presented data let us conclude that D.W. is able to control his pupil directly. Both, D.W.'s perception and its observable consequences suggest that his behavior to control pupil size is indistinguishable from a direct manipulation. Speculating about the genesis of the phenomenon, it is conceivable that D.W. made use of a cascade of learning processes, some of which might have been facilitated by indirect strategies. Today however, we believe that D.W. is able to use direct action that is conscious and voluntary, that is, having a high level of control (Huestegge et al., 2019). This suggests that much more effective ways of learning how to control one's pupil size must exist than the indirect ones put forward so far (e.g., Ehlers et al., 2016; Ekman et al., 2008; Laeng and Sulutvedt, 2014). While none of the three indirect factors for manipulating pupil size could account for the observed pupillary movements fully, the additionally uploaded interview, optometric testing, and neuroimaging results suggest an involvement of accommodation in the process or during the learning history. Markedly improved visual acuity at and beyond the near point during voluntary constriction, however, argues (see Section 3.3) for D.W.'s ability to affect the pupillary musculature beyond accommodation.

5.1. Conclusion

While the above speculations still await empirical validation, for the time being the present single case can be summarized as follows: (1) In contrast to the canonical understanding of pupillometry, the here presented case either uses a direct way to affect pupil size or an indirect way that is indistinguishable from a direct way; with about 2.4 mm for constriction and about 0.8 mm for dilation, the height of effects being substantial, and latencies unparalleled in existing research. (2) It is suggested by present data, that the indirect strategies tested here cannot entirely account for these observations. While constrictions might be partially a consequence of shifts in accommodation, dilations cannot be explained by any indirect strategy. Substantial improvements in vision achieved by voluntary constriction at maximal accommodation further suggest that D.W. is able to constrict his pupil voluntarily and directly. (3) As it presently stands, voluntary dilation and constriction appear as a product of direct will, i.e., volitional impulses that stem from aspects of the dorsolateral prefrontal cortex and are mediated by premotor areas including the supplementary motor area.

5.2. Further research

However, as we were not in the position to mechanistically outline how the full final pathway is innervated or inhibited, this conclusion has certainly to remain tentative. It is still possible that we have overseen something, conscious or unconscious to our present case, which helps him indirectly to produce the current phenomenon. Consequently, we fully acknowledge what Loewenfeld (1993) p. 649, has written, that she has "(…) found most of the instances described in the literature as "voluntary pupil movements" to be such indirect results either of - conscious or unconscious - accommodative efforts, leading to pupillary constriction and redilation, or (more often) of mental efforts and imaginations, causing pupillary dilation (…)". However, so far, we do not have substantial evidence that any of these putative indirect strategies would apply for the present case, suggesting that voluntary direct control of the pupil size is possible. At this point, we hope to initiate a scientific discussion about unthought, additional indirect possibilities that could explain the present phenomenon and on how direct control of the pupillary musculature can be learned. As a first step in this direction, we would recommend to visit the website to which we have uploaded a real-time video of the present case.

Appendix A. Supplementary data

Data from the experiments, including for the pupillometric and optometric assessment of the right eye, as well as a video clip of the phenomenon, the scripts for experiments, signal processing and statistical analyses may be retrieved from the open science framework via https://osf.io/7uf4x/. We also uploaded pupillary data without baseline correction, showing a similar pattern of results. Gaze position over time, suggests no substantial inward or outward rotation of the eye during active pupil size manipulation relative to the control conditions. Furthermore, we provide a detailed interview with D.W., describing his ability, the associated sensations, as a series of related questions and answers. Honouring the quality of pioneers in pupillometry, we here also uploaded scans of the respective articles by Bekhterev, Goldflam, and Petrovic & Tschemolossow that could not be found online. Supplementary data to this article can be found online at doi: https://doi.org/10.1016/j.ijpsycho.2021.08.001.

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