Received: 8 July 2020 | Revised: 23 September 2020 | Accepted: 29 October 2020

DOI: 10.1111/psyp.13729

ORIGINAL ARTICLE

PSYCHOPHYSIOLOGY SPR WILEY

Effects of vocal demands on pupil dilation

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Funding information
This research was funded by the European Research Council (grant number 677819 awarded to B. F. Händel)

Abstract

Pupil dilation is known to be affected by a variety of factors, including physical (e.g., light) and cognitive sources of influence (e.g., mental load due to working memory demands, stimulus/response competition etc.). In the present experiment, we tested the extent to which vocal demands (speaking) can affect pupil dilation. Based on corresponding preliminary evidence found in a reanalysis of an existing data set from our lab, we setup a new experiment that systematically investigated vocal response-related effects compared to mere jaw/lip movement and button press responses. Conditions changed on a trial-by-trial basis while participants were instructed to keep fixating a central cross on a screen throughout. In line with our prediction (and previous observation), speaking caused the pupils to dilate strongest, followed by nonvocal movements and finally a baseline condition without any vocal or muscular demands. An additional analysis of blink rates showed no difference in blink frequency between vocal and baseline conditions, but different blink dynamics. Finally, simultaneously recorded electromyographic activity showed that muscle activity may contribute to some (but not all) aspects of the observed effects on pupil size. The results are discussed in the context of other recent research indicating effects of perceived (instead of executed) vocal action on pupil dynamics.

KEYWORDS

blink rate, eye movements, movement interaction, pupil dilation, vocal responses

1 | INTRODUCTION

Apart from its sensitivity to physical sources of influence (e.g., light), pupil dilation has been shown to be affected by mental processing load (e.g., Hess & Polt, 1964; see Laeng et al., 2012; Mathôt, 2018). Specifically, pupils are sensitive to executive or working memory load (e.g., Beatty & Kahneman, 1966; Chatham et al., 2009; Karatekin et al., 2004; Katidioti et al., 2014) and to the relation between stimuli and responses as measured by the Stroop task (Laeng et al., 2011) or by a finger response-cuing paradigm (Moresi et al., 2008). Pupil size was also linked to the preparation and execution of self-triggered finger flexions. Specifically, pupil diameter increases for more complex movements (Richer & Beatty, 1985). In addition, hand movement imagery was related to an increase in pupil diameter compared to no task (Rozado et al., 2015). It was also shown that pupil size during imagery was slightly smaller, but not significantly different to real executed hand movements (O'Shea & Moran, 2016).

Recently, it has additionally been demonstrated that pupils are possibly related to speech or speech processing, as pupil dilation increased when listening to vocal as opposed to instrumental music (Weiss et al., 2016). However, the question of whether producing instead of listening to vocal output can also affect pupil responses has not been systematically addressed yet. While the presence (vs. absence) of vocalization demands should generally increase executive load, we here for the first time study specific effects of vocalization, and in particular the motor aspect of it, on pupil dynamics.

On a general level, the idea that different behavioral systems may strongly affect each other is supported by research on cross-modal multiple action control. Specifically, it has been shown that eye-related responses such as saccade latencies interact with even simple additional concurrent action demands in other effector systems such as a manual key press or a basic vocal response (Huestegge, 2011; Huestegge et al., 2014; Huestegge & Koch, 2013; Pieczykolan & Huestegge, 2014). However, up to now, studies on the effects of vocal actions, that is, the motor activity during speaking, on pupil size are still lacking.

Taking the idea of a strong interaction between various behavioral domains seriously, we decided to additionally assess the blinking behavior during vocalizations. Indeed, similar to pupil dilation, blink rate has also been discussed as an index of perceptual and cognitive load (e.g., Fogarty & Stern, 1989; VanderWerf et al., 2003), and has also been studied in the context of verbal (dyadic) communication (e.g., Bentivoglio et al., 1997). However, corresponding research is less extensive and systematic than that on pupil dilation, and research on the interaction between pupil and blink responses in particular is even more rare (e.g., Siegle et al., 2008).

In a first step toward addressing the influence of vocalization on pupil size and blink rate, we reanalyzed a set of data from a previous, unpublished study that was not originally designed to address effects of vocal demands on pupil responses. Participants (N = 18, 13 female, mean age = 23, SD = 2.9) randomly switched between single manual (left/right key press), single vocal (uttering the words “left”/”right”), and dual (manual + vocal) response demands on a trial-by-trial basis while fixating a central fixation cross (green on black background) throughout. The pitch of a lateralized tone (200, 600, and 3,200 Hz) indicated the response condition (single manual, single vocal, vocal + manual; mapping counterbalanced across participants), while tone presentation side (via headphones) indicated the response identity (e.g., tone on left ear indicated to execute a left key press, saying “left,” or doing both). Each trial lasted 3 s, with 540 trials in total. An EyeLink II eye tracker (500 Hz, SR Research, Canada) was used. Results revealed an effect of response condition on pupil dilation, $F(2, 34) = 6.64$, $p = .004$, $\eta^2_{\mathrm{p}} = 0.281$: Pupils dilated more in both the vocal + manual and single vocal conditions than in the single manual condition (p = .023, p = .011; see Figure 1). Thus, vocal demands in terms of corresponding motor activity related to the mouth and vocal tract appeared to increase pupil dilation. An additional analysis of blink rates also revealed an effect of response condition, $F(2, 34) = 4.36$, $p = .021$, $\eta^2_{\mathrm{p}} = 0.204$: Conditions involving vocal demands involved higher blink rates than the single manual condition (although post hoc contrasts revealed that only the difference between the single manual and the dual condition was significant, p = .027).

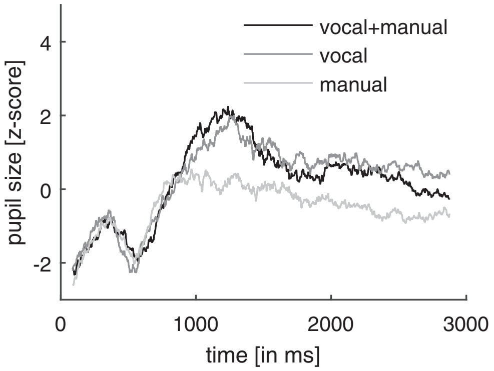

FIGURE 1 Exploratory analysis of a previous data set showing pupil dynamics within each trial as a function of response condition. We plotted the mean pupil diameter (here: z-standardized across all conditions) as a function of time elapsed in a trial. All trials involving a blink (65.8%) were removed for this analysis. This rather strict criterion was applied to ensure that blinks cannot possibly contribute to the observed effects. Pupil diameter was baseline corrected (based on the dilation data during the first 100 ms of each trial prior to stimulus onset). Thus, the dependent variable was the maximum baseline-corrected diameter increase (measured in arbitrary raw data units as provided by the eye tracker) within each (error-free) trial. Note that the lines diverge at around 1 s (i.e., around the time of the mean vocal response onset of 1,150 ms), and the effect extended until the end of the trial

Based on this reanalysis of previous data (which served as an exploratory starting point to come up with specific hypotheses), we setup a new experiment to rigorously test whether and how vocal demands indeed increase pupil dilation. This new experiment erased several limitations of the previous (exploratory) reanalysis study. First, trial duration was increased to ensure that an increase in pupil size due to the task will return to baseline before the start of the next trial. Second, a proper baseline condition without any response demands was added, and third, a pure motor condition requiring mouth movements without auditory output was included to possibly pinpoint other types of influence of vocalization on pupil dilation and to exclude any effects that might merely be driven by differences in overall task demands. Specifically, we included the following conditions: Two vocal conditions targeting different mouth movements (lip loud: uttering “boo” and jaw loud: uttering “mmh” while clenching teeth), three nonvocal movements (lip silent: lip movements of “boo” without producing sound, jaw silent: clenching teeth without producing sound, and key press: finger movement) and a baseline condition (no response at all). We hypothesized that pupil dilation should be greatest for the two vocal response conditions, followed by the nonvocal movement conditions, and finally, the baseline condition without any response requirements.

2 | METHOD

2.1 | Participants

Twenty-five participants (20 female, mean age: 24.2, *SD*: 5.2) took part in the study. A power analysis based on the effect size in the previous data set (see above) revealed that this sample size is sufficient to detect a pupil size effect with >95% probability. One additional participant was excluded due to the execution of >55 blinks/minute. All gave their written informed consent and received payment or study credit for their participation. The study was conducted in line with the European data protection rules.

2.2 | Apparatus and stimuli

Participants sat in a moderately lit room in front of a standard computer screen wearing Sennheiser PMX 95 headphones. Their forehead touched a bar fixing the distance of the eyes to the screen and eye tracker. Binocular eye movements were collected at a sampling rate of 500 Hz using an EyeLink II (SR Research, Canada). A single key was placed on the table connected to a BBTK response box (model: K-RB1-4; The Black Box ToolKit Ltd, UK). A green fixation cross (0.6°) was continuously presented on black background at the center of the screen. Auditory instruction words ("lip loud," "lip silent" "jaw loud," "jaw silent," "key," and "pause" in German) were presented (500 ms) prior to a go signal (frequency: 300 Hz, 50 ms). To record electromyographic (EMG) activity in the face, three electrodes were placed around the right eye, another one below the left lip corner, and a last one above the left musculus masseter. Reference and ground electrodes were fixed on the earlobes (Figure 2). The experimental program was implemented using Psychtoolbox-3 in MATLAB R2015a (Brainard, 1997; Pelli, 1997; The MathWorks Inc., Natick, MA, USA).

2.3 | Procedure

Each trial involved the presentation of one auditory instruction followed by the go signal after 1,000 to 1,500 ms (jittered in steps of 100 ms). The next trial started after four additional seconds. Oral presentation of the words "lip loud" or "lip silent" signaled to utter the word "boo" vocally or without producing sound. The instruction "jaw silent" referred to clenching one's teeth, while "jaw loud" required saying "mmh" in addition. The word "key" indicated pressing a response button with a finger, and the word "pause" suggested to withhold any response (baseline). Each participant completed 15 blocks consisting of 30 trials each. Within a block, each condition was performed five times in randomized sequence. Prior to each block, subjects underwent a calibration routine for the eye tracker. Participants underwent (at least once) a practice block, in which all conditions occurred twice. The experiment lasted approximately 50 min.

2.4 | Blink detection

Whenever the z-transformed pupil diameter decreased more than two standard deviations (*SD*) away from the mean in both eyes, a blink was detected. This time range was extended until the z-transformed pupil data of both eyes reached a threshold of one *SD* away from the mean (verification of our custom blink detection by comparing it to the internal EyeLink blink detection as well as EOG blink detection is presented in Supporting Information). Blinks occurring less than 100 ms apart from each other were combined. Those that lasted less than 50 ms or more than 500 ms were discarded.

2.5 | Data analysis

MATLAB R2015a (The MathWorks Inc., Natick, MA, USA) was used for data analysis. Pupil loss, for example, due to blinks, was linearly interpolated before averaging over both eyes. Linear interpolation was performed from the time point of 20 ms before data loss until the time point of 20 ms after data loss. Trials that included more than 30% of interpolation were excluded (maximally 38/450 trials). Pupil diameter was baseline corrected by subtracting the mean pupil size of the time interval between −1,000 and −900 ms before the go signal. We used the maximum baseline-corrected diameter increase as dependent variable,

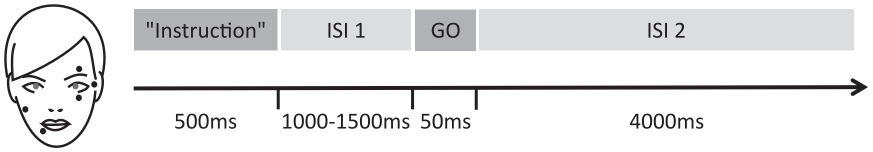

FIGURE 2 Electrode placement and trial structure. After the auditory instruction, subjects had to wait for a jittered time period (Interstimulus-Interval 1) until the go signal, after which the movement (based on the instruction) should be executed. Trials ended four seconds after the go signal (ISI 2)

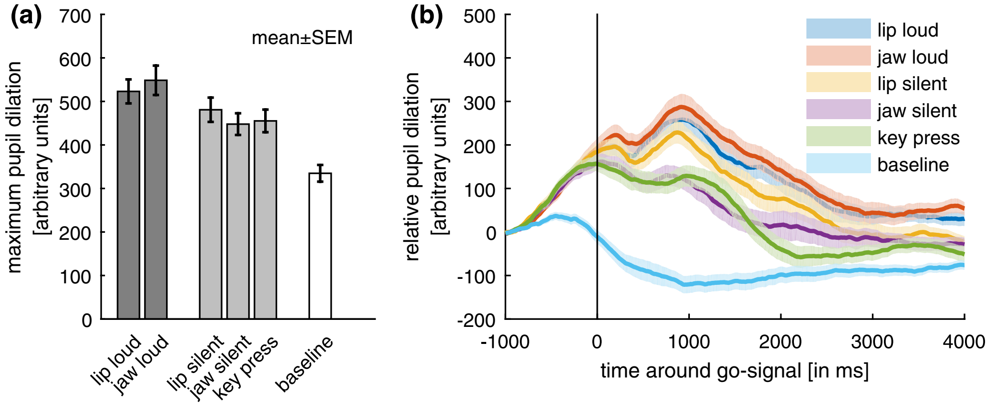

FIGURE 3 (a) Maximum pupil dilation for the six different conditions (± *SEM*). Statistical comparisons between the individual conditions are presented in Table 1. (b) Mean pupil diameter for the different conditions relative to the first 100 ms of the graph. Shaded areas represent ± *SEM*

TABLE 1 *p* values of the Bonferroni-adjusted post hoc tests comparing the maximum pupil dilation across conditions where * indicates statistical significance with $p < .05$

	Lip loud	Jaw loud	Lip silent	Jaw silent	Key press	Baseline
Lip loud	–	1	0.222	0.017*	0.051	<.001*
Jaw loud	–	–	0.002*	<0.001*	0.005*	<.001*
Lip silent	–	–	–	0.837	1	<.001*
Jaw silent	–	–	–	–	1	<.001*
Key press	–	–	–	–	–	<.001*

which enables an analysis over the complete time range of a trial instead of manually selecting a time window. However, Supporting Information also includes an analysis of mean baseline-corrected pupil diameter between −1,000 and 2,000 ms (revealing similar results). For each participant, we excluded trials that showed a maximum diameter increase that was three times larger than the interquartile range (maximally 5/450 trials).

Blink rate was calculated over the time window from −1,000 to 4,000 ms. Continuous blink graphs were obtained by coding all time points with zeros, whereas blinks were marked with ones (Siegle et al., 2008). These binary coded trials were averaged and baseline corrected by subtracting the mean of −1,000 to −900 ms before the go signal to obtain a mean proportion of blinks at each time sample.

The EMG signal of one participant was excluded due to technical problems. For all other data sets, each channel of the EMG was normalized by subtracting the mean of the other channels. After that, the signal was band-pass filtered (20–90 Hz) and the Hilbert transformation was applied. This signal was again low-pass filtered (10 Hz) and baseline corrected by subtracting the mean of −1,000 to −900 ms before the go signal. Graphs show the signal change of the electrode that was placed close to muscles executing the movement (electrode below the lip for lip movements, electrode on the musculus masseter for jaw movements).

3 | RESULTS

3.1 | Pupil dilation

Pupil size increased after the instruction word, but quickly decreased during the baseline condition ("pause"). In contrast, pupil size increased until after the go signal for all other conditions (Figure 3). A repeated-measures ANOVA using the maximum pupil dilation as dependent variable revealed a significant main effect of conditions ($F(5,120) = 36.74$, $p < .001$, $\eta_p^2 = 0.605$). Bonferroni-adjusted post hoc tests confirmed our main hypothesis: The pupil dilation increase was significantly greater for both vocal tasks ("lip loud" and "jaw loud") and for nonvocal movements ("lip silent," "jaw silent," and "key press") compared to the baseline condition ("pause"). The two vocal tasks did not significantly differ between each other. The same holds for the three nonvocal tasks, suggesting that the "key press" condition was comparable to the other (lip/jaw) silent conditions. Critically, maximum pupil diameter for "jaw loud" was significantly greater than for "jaw silent" and "lip silent." The diameter was also significantly larger for "lip loud" than for "jaw silent." Only the tendency toward a greater diameter for "lip loud" than for "lip silent" failed to reach the significance threshold. Detailed *p* values are depicted in Table 1.

3.2 | Blinks

First, we calculated the number of blinks per minute for each condition. A repeated-measures ANOVA with the number of blinks per minute as dependent variable revealed a significant difference between conditions ($F(5,120) = 2.94$, $p < .033$, $\eta^2_\text{p} = 0.109$, $\varepsilon = 0.662$ (Greenhouse–Geisser correction applied). Bonferroni-adjusted post hoc tests only showed a significantly higher blink rate during vocal conditions ("lip loud" and "jaw loud") compared to the "jaw silent" condition ($p < .008$ and $p < .034$), while all other comparisons were nonsignificant.

Second, we analyzed blink dynamics (Figure 4), which can be described along three sub-patterns. While a peak after the instruction word could be detected in all conditions, this increase was strongest (and the only peak) in the baseline condition. In the key press condition, a second, strong and rather long-lasting increase (between 500 and 1,500 ms) could be identified following the go signal. In contrast, all conditions involving facial muscle activity (both loud and silent) showed two local peaks after the go signal. The first was located at approximately 500 ms, the second at 1,500 ms. While the first seemed rather comparable in size and shape between verbal conditions, the second peak varied considerably in its latency and strength. In sum, the blink analysis suggests that although the overall frequency of occurrence does not strongly differ between conditions, the timing of the blinks appears to be quite sensitive to the different contextual (facial and manual) motor demands.

3.3 | Electromyographic activity

We measured EMG activity to approximate the on- and offset of mouth movements as well as to assess differences between loud and silent conditions. Interestingly, blinks seem to have occurred either before or at the beginning of the mouth movement (500 ms after the go signal) or after the end of the movement (around 1,500 ms). Comparing loud and silent conditions revealed a stronger and longer lasting EMG-signal during "lip loud" compared to "lip silent," but the signal was highly similar during "jaw loud" and "jaw silent" conditions (Figure 5).

4 | DISCUSSION

The present study focused on the analysis of pupil dilation as a function of different types of vocal-related demands. Our reanalysis of a previous, existing data set suggested that vocalization indeed leads to a significant increase in pupil dilation compared to a condition without vocal demands. We replicated these findings in a follow-up study, and to pinpoint the underlying mechanisms and to exclude a range of potential confounds, we included several control conditions.

The experiment showed that pupil responses were indeed sensitive to the presence of vocal demands: Conditions with vocal demands were associated with the greatest increase in pupil dilation, followed by the conditions requiring a facial movement without oral sound production. All of the crucial comparisons were significant ("jaw loud" vs. "jaw silent," "jaw loud" vs. "lip silent," "lip loud" vs. "jaw silent") except for one contrast ("lip loud" vs. "lip silent"), which nevertheless pointed into the expected direction. The manual movement condition was comparable to the silent facial movement conditions. Pupil dilation was minimal in the baseline condition without any response requirements. As vocal demands typically consist of at least two components, namely mouth-related movements and the production of sound (involving the vocal tract), the results suggest that both aspects contribute to the observed overall effects of vocal demands on pupil dilation.

Concerning lip movements, the difference in amplitude of the EMG signal between loud and silent lip conditions might be explained by the direct involvement of the lips during sound production known as bilabial plosive (Ladefoged & Maddieson, 1996). Uttering "boo" during the lip loud condition involves constricting the airflow out of the mouth by pressing

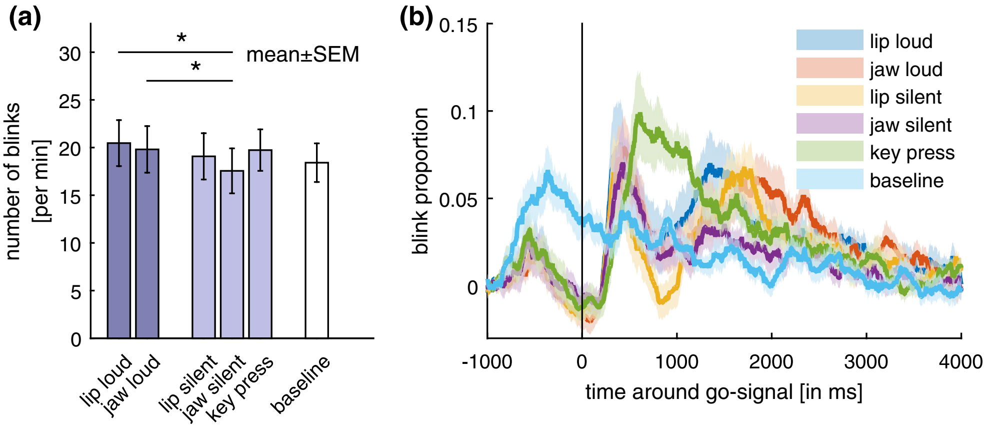

FIGURE 4 (a) Mean number of blinks per minute for the six different conditions (± *SEM*). (b) Mean averaged blink proportion of the conditions as a function of time. Shaded areas represent ± *SEM*

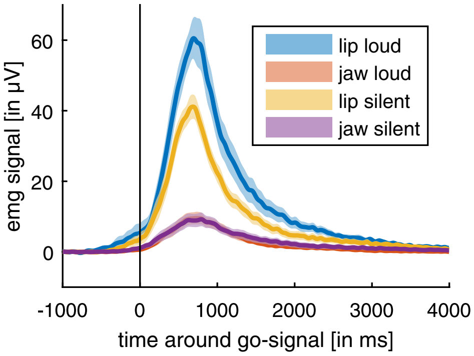

FIGURE 5 Electromyographic activity during mouth movements. While the activity seems to differ between silent and loud lip movement conditions, they highly overlap during jaw movements. Please note that the difference in peak amplitude between lip and jaw movements is not informative, since the signal stems from different electrodes

the lips together. Since the airflow is likely less present during the silent condition, this likely explains the difference in motor activity. In contrast, jaw muscles are not involved in sound articulation of "mmh" (bilabial nasal articulation, Ladefoged & Maddieson, 1996), thereby resulting in a highly similar amplitude in the EMG signal between loud and silent conditions. Due to our electrode placement, we cannot specify the influence of motor activity of the vocal tract, but we assume that there should also be a difference between loud and silent conditions. The difference in pupil diameter between all loud conditions and all silent conditions (except for "lip loud" vs. "lip silent") suggests that not only the movement itself, but also the articulation of sound, the facial movement and the motor activity of the vocal tract, increase the pupil diameter.

While our overall result pattern is well in line with our predictions, one might still further speculate why the pupil dilation between the lip loud and lip silent condition did no significantly differ. O'Shea and Moran (2016) suggested that mental imagery of actions may have similar effects on the pupil as "real" actions. Thus, mental imagery of producing "boo" while moving the lips accordingly in the silent condition might have increased pupil size similar to the real utterance of "boo." This might also explain the difference in the nature of lip and jaw movements. While clenching ones teeth (jaw movement) is not clearly associated with a sound, the lip movements are clearly associated with the sound "boo." Overall, while the complexity of the task itself (detect a cue and choose a simple motor output as response) is roughly comparable for all task conditions, apparently even slight differences in motor output demands lead to a change in pupil dilation. Therefore, we advise to be cautious when using pupil size as a marker of cognitive aspects of a task whenever differences in motor activity exist between task conditions.

While in a future study one might want to additionally assess whether a sound-inducing button press or nonvocal auditory input would lead to a similarly strong pupil dilation response, previous research already demonstrated that pupil dilation is greater for listening to vocal than to instrumental music (Weiss et al., 2016) suggesting a specific role of vocalization rather than auditory input per se. Interestingly, our setup did not include social or higher order cognitive aspects, since neither was the elicited sound meaningful, nor was any sort of communication involved. Therefore, it is neither the interpretation of the vocal input nor the social context that leads to the modulation of pupil dilation here. Our findings might rather point to an interaction between auditory vocal input and the motor aspect of vocalization, such that the increased pupil dilation for listening to vocal compared to instrumental music (Weiss et al., 2016) might depict common (and automatic) coding of vocal perception and action (Hommel et al., 2001).

It is further important to consider the modulation of the pupil diameter in the light of blinking. Blinks change the light input, thereby leading to a slight change in pupil size. Additionally, blinks can lead to a miscalculation of pupil size if the algorithm used by the eye tracker does not fully take the pupil coverage during a blink into account. Since we did not find consistent significant differences in the number of blinks between vocal and baseline conditions (unlike the substantial corresponding effect in pupil diameter), blinks are very unlikely to account for the reported effects on pupil dilation here. This is further confirmed by the exploratory data reanalysis (presented in the introduction), in which we deliberately decided not to implement any data interpolation regarding blinks and only analyzed blink-free trials to minimize any possibility that the effect on pupil size might be driven by blinks. The results were highly similar to the results of our newly designed experiment, where we generously interpolated blinks. While this again strongly suggests that blinking behavior cannot account for the observed effects on pupil dilation, a replication study of the present experiment might include an explicit instruction to avoid blinking. However, while blinking does not seem to drive the pupil dilation changes during vocalization, we observed a complex temporal pattern of blinking that is clearly distinct for vocal motor output compared to, for example, a button press. Such time-critical motor-based modulation can be of importance for studies on blink rate during verbal (dyadic) communication. For such studies, which assess blink rates during a conversation (e.g., Bentivoglio et al., 1997) or eyeblink behavior at breakpoints of speech (Nakano & Kitazawa, 2010), it appears important to consider that vocal demands per se can affect ocular parameters on a fine-grained temporal scale.

ACKNOWLEDGMENT

Open access funding enabled and organized by Projekt DEAL.

AUTHOR CONTRIBUTION

Mareike Brych: Conceptualization; Formal analysis; Investigation; Methodology; Project administration;

Software; Validation; Visualization; Writing-original draft; Writing-review & editing. **Barbara F. Händel:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Methodology; Project administration; Supervision; Writing-original draft. **Eva Riechelmann:** Conceptualization; Investigation; Methodology; Project administration; Resources. **Aleksandra Pieczykolan:** Formal analysis; Investigation; Methodology; Resources. **Lynn Huestegge:** Conceptualization; Data curation; Methodology; Project administration; Resources; Supervision; Writing-original draft; Writing-review & editing.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Brych M, Händel BF, Riechelmann E, Pieczykolan A, Huestegge L. Effects of vocal demands on pupil dilation. *Psychophysiology*. 2021;58:e13729. https://doi.org/10.1111/psyp.13729