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OBSERVATION

Pupils Dilate for Vocal or Familiar Music

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Previous research reveals that vocal melodies are remembered better than instrumental renditions. Here we explored the possibility that the voice, as a highly salient stimulus, elicits greater arousal than nonvocal stimuli, resulting in greater pupil dilation for vocal than for instrumental melodies. We also explored the possibility that pupil dilation indexes memory for melodies. We tracked pupil dilation during a single exposure to 24 unfamiliar folk melodies (half sung to *la la*, half piano) and during a subsequent recognition test in which the previously heard melodies were intermixed with 24 novel melodies (half sung, half piano) from the same corpus. Pupil dilation was greater for vocal melodies than for piano melodies in the exposure phase and in the test phase. It was also greater for previously heard melodies than for novel melodies. Our findings provide the first evidence that pupillometry can be used to measure recognition of stimuli that unfold over several seconds. They also provide the first evidence of enhanced arousal to vocal melodies during encoding and retrieval, thereby supporting the more general notion of the voice as a privileged signal.

Keywords: melody, timbre, arousal, memory, pupil dilation

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Vocal sounds are biologically and functionally significant; therefore, it is not surprising that they elicit distinctive neural (Belin, Zatorre, & Ahad, 2002), electrophysiological (Bruneau et al., 2013; Charest et al., 2009), and behavioral responses (Agus, Suied, Thorpe, & Pressnitzer, 2012). Neural responses to vocal sounds with social or communicative significance (e.g., speech, laughter) are also distinct from responses to other vocal sounds (e.g., coughs, sneezes; Shultz, Vouloumanos, & Pelphrey, 2012). In view of the distinctive processing of vocal signals and the ubiquity of vocal music within and across cultures, the almost exclusive reliance on instrumental stimuli in music-cognition research is surprising, perhaps even counterproductive. In fact, adults and children remember vocal renditions of melodies (sung to *la la*) more readily than instrumental renditions with the same pitch level and timing (Weiss, Schellenberg, Trehub, & Dawber, 2015a; Weiss, Trehub, & Schellenberg, 2012). Moreover, pianists exhibit a comparable vocal melody advantage and no advantage for piano melodies over other instrumental melodies (Weiss, Vanzella, Schellenberg, & Trehub, 2015b), ruling out potential contributions of timbre familiarity and sensorimotor activation (e.g., Lévêque & Schön, 2015). Here we explore the possibility that the heightened salience of vocal melodies would be reflected in greater pupil dilation.

We use pupil dilation as an index of the relative salience of vocal melodies because of its links to emotional arousal (Sterpenich et al., 2006), skin conductance (Bradley, Miccoli, Escrig, & Lang, 2008), and salience ratings of brief (500-ms) auditory stimuli (Liao, Kidani, Yoneya, Kashino, & Furukawa, 2016). Task-evoked pupillary activity provides an online measure of arousal or engagement with a stimulus or task (Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2013; Kang, Huffer, & Wheatley, 2014). In nonhuman species, changes in pupil diameter are correlated with activity in the locus coeruleus (LC), the source of norepinephrine (NE) in the brain (Aston-Jones & Cohen, 2005). NE emitted by the LC influences autonomic arousal, exogenous attention, and memory consolidation (Sara & Bouret, 2012).

According to the GANE (glutamate amplifies noradrenergic effects) model, task-evoked LC activity releases NE, which interacts with local glutamate concentrations to enhance the perception and consolidation of highly salient stimuli (Mather, Clewett, Sakaki, & Harley, 2015). Human pupil dilation covaries with blood-oxygen-level dependent (BOLD) responses in the vicinity of the LC (Murphy, O'Connell, O'Sullivan, Robertson, & Balsters, 2014), suggesting its utility as an index of LC activity. There are suggestions that arousing instrumental music influences pupil dilation (Gingras, Marin, Puig-Waldmüller, & Fitch, 2015), but it is unclear whether vocal and instrumental music have different arousal consequences. In line with the GANE model, vocal music

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should enhance the release of phasic NE, as revealed by greater phasic pupil dilation.

Pupillometry can also index recognition memory, as reflected in greater pupil dilation for familiar than for novel visual (Heaver & Hutton, 2011; Kafkas & Montaldi, 2012) and auditory (Otero, Weekes & Hutton, 2011; Papesh, Goldinger, & Hout, 2012) stimuli. These studies of recognition memory have used the task-evoked pupillary reflex (TEPR), a rapid-onset response that peaks within a few seconds (Papesh & Goldinger, 2015). However, it is unclear whether pupil dilation can index memory for melodies that unfold over several seconds, necessitating arousal responses well outside of the time frame of the TEPR. If pupil dilation beyond the initial reflex is sensitive to the effects of recognition, then it would have methodological as well as theoretical implications, providing an alternative to gating tasks for assessing the time course of music recognition (e.g., Dalla Bella, Peretz, & Aronoff, 2003) and shedding light on the arousal consequences of recognition and stimulus salience. It would also provide the first evidence that pupillometry—an objective measure—can be used to examine the recognition of stimuli, auditory or otherwise, that unfold over time.

In the present study, we used vocal and piano melodies to tease apart the effects of stimulus salience and recognition on arousal, as reflected in pupil dilation. Music listening evokes rapid evaluation of surface features, including timbre (Agus et al., 2012), which can vary in salience, but recognizing a melody as familiar (Dalla Bella et al., 2003) requires considerably more time than recognizing a word or picture as familiar. In previous research on word or picture recognition, a brief time window was able to capture pupil dilation responses to surface features and stimulus identity (e.g., Heaver & Hutton, 2011; Kafkas & Montaldi, 2012; Otero et al., 2011; Papesh et al., 2012). It is important to establish whether recognition processes that occur beyond the time frame of the TEPR have consequences on arousal. With respect to the enhanced processing of vocal melodies (Weiss et al., 2012, 2015a, 2015b), we asked whether vocal melodies elevate arousal relative to piano melodies for the first few seconds and whether arousal remains elevated for the duration of the melody.

Method

Participants

Our sample included 50 young adults (20 male, $M = 19.8$ years, $SD = 1.5$), recruited without regard to music lessons ($M = 3.7$ years, $SD = 4.2$), who had normal hearing and normal (corrected or uncorrected) vision (self-report). Additional participants were excluded for insufficient pupillary data ($n = 3$, see supplementary information online), memory performance 2 *SD*s below the mean ($n = 3$), equipment malfunction ($n = 8$), or eye fatigue ($n = 3$).

Stimuli

The stimuli were 48 excerpts of folk melodies, 12.8–20.5 s in duration taken from Weiss et al. (2015b), with one version of each melody sung to *la la* and another performed on piano. Vocal melodies were pitch- and time-corrected (Melodyne software, Celemony, Munich, Germany), and all melodies were amplitude normalized (root mean square).

Apparatus

Participants were seated individually in a dimly lit room. A chinrest preserved constant eye distance (60 cm) from the monitor (ELO Touchsystems, Milpitas, CA). Pupillary data were collected with an SR Research EyeLink II head-mounted eye-tracker (250 Hz sampling rate, right eye; http://www.sr-research.com/pdf/elII_table.pdf; Mississauga, Ontario, Canada). The eye-tracker measured dilation in arbitrary units that were normalized to a baseline preceding each trial, yielding percentage changes in pupil dilation relative to baseline (e.g., van Rijn, Dalenberg, Borst, & Sprenger, 2012). Experiment Builder (version 1.10) was used to program the task on a Dell computer (Windows XP). Stimuli were presented at a comfortable listening level, approximately 65 dB, via headphones (Vic Firth Stereo Isolation or Sony MDR-V300) placed over the head-mounted eye-tracker (see supplementary information online for details).

Procedure

Listeners were asked to minimize blinking and to fixate on a small cross at the center of the screen during each trial. At exposure, they heard 24 trials of piano and vocal melodies (12 per timbre) in random order. Each melody was preceded by 5-s silence, with the final second providing a baseline for that trial. After hearing each melody, listeners indicated how much they liked it on a 5-point scale. After the exposure phase, they completed a background questionnaire for 5–10 min. They then heard the same 24 old melodies intermixed with 24 new melodies (half voice, half piano), with order of presentation randomized, and indicated whether they had heard them before on a 7-point scale (1 [*definitely new*] to 7 [*definitely old*]). Assignment of excerpts to timbre (piano, vocal) and exposure/test or test only was individually randomized.

Results

Behavioral Responses

Exposure phase. Mean liking ratings, averaged over 12 responses per participant per timbre (one trial from one participant excluded because of error), were calculated separately for vocal and piano melodies. Vocal melodies ($M = 3.01$, $SD = 0.74$) were liked less than piano melodies ($M = 3.62$, $SD = 0.56$), $t(49) = 4.70$, $p < .001$, Cohen's $d = 0.67$, as in previous research (Weiss et al., 2012, 2015a, 2015b).

Test phase. Mean recognition ratings were averaged over 12 responses per participant per condition (one trial excluded from two participants): old voice, old piano, new voice, and new piano (see Figure 1). An analysis of variance (ANOVA) with exposure level (old, new) and timbre (voice, piano) as repeated measures revealed significant main effects of exposure, $F(1, 49) = 284.05$, $p < .001$, partial $\eta^2 = .85$, and timbre, $F(1, 49) = 37.99$, $p < .001$, partial $\eta^2 = .44$, as well as a significant interaction, $F(1, 49) = 6.03$, $p = .018$, partial $\eta^2 = .11$. The interaction confirmed that the difference between old and new melodies varied across timbres, indicating better recognition of vocal over piano excerpts as in previous research (Weiss et al., 2012, 2015a, 2015b). Analyses of d' scores yielded comparable results (see supplementary information online).

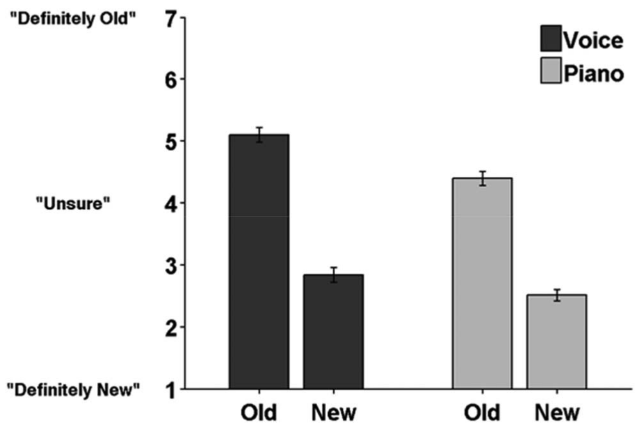

Figure 1. Mean recognition ratings as a function of timbre and previous exposure (old, new). The difference between old and new melodies was greater for vocal than for piano melodies, indicating enhanced recognition for the vocal melodies. Error bars are *SEM*.

Pupil Dilation

Details on preprocessing are provided in the online supplementary information. We examined pupillary changes relative to the 1-s baseline preceding each melody.

Exposure phase. Timbre effects were expected within the TEPR. After ascertaining that the TEPR for melodies occurred within 6 s of melody onset (see supplementary information online), we evaluated pupil dilation for this period. Data were averaged within 1-s bins, yielding six bins (0–1 s, 1–2 s, etc.). A repeated-measures ANOVA as a function of time bin (1–6) and timbre (voice, piano) revealed main effects of timbre, $F(1, 49) = 5.44$, $p = .024$, partial $\eta^2 = .10$, and time, $F(5, 245) = 37.89$, $p < .001$, partial $\eta^2 = .44$, but no interaction, $p > .2$. As shown in Figure 2, vocal melodies elicited larger pupil dilation than piano melodies, and the magnitude of the effect (i.e., vertical distance between red and blue lines) was similar across time bins.

Test phase. Because melody recognition is unlikely to occur within 6 s, we expanded the area of interest to the 12 s available for all melodies. For each participant, pupil dilation relative to baseline was calculated as a function of exposure (old, new), timbre (voice, piano), and 12 time bins (see Figure 3). A repeated-measures ANOVA revealed a significant main effect of timbre, $F(1, 49) = 5.66$, $p = .021$, partial $\eta^2 = .10$, but no interactions involving timbre, *ps* $> .2$. Pupil dilation was greater for the voice than for the piano, as at exposure, and this effect was not moderated by exposure or time. By contrast, main effects of exposure level, $F(1, 49) = 4.94$, $p = .031$, partial $\eta^2 = .09$, and time bin, $F(11, 539) = 37.96$, $p < .001$, partial $\eta^2 = .44$, were qualified by an interaction between exposure and time, $F(11, 539) = 4.12$, $p = .007$, partial $\eta^2 = .08$. Follow-up comparisons of old and new trials (collapsed across timbres) revealed no difference in the first 5 time bins, *ps* $> .1$, marginally greater dilation for old melodies in time bin 6, $p = .066$, and significantly greater dilation in time bins 7–12, *ps* $< .025$. In short, old vocal and piano melodies evoked greater pupil dilation after participants heard a sufficient number of notes to identify the melodies as familiar.

Discussion

Our study is the first to compare a physiological indicator of arousal during initial exposure to vocal and instrumental (i.e., piano) melodies and during a subsequent recognition test. The findings revealed that pupillometry is sensitive to differences in timbre and familiarity and that these two variables function independently rather than interactively. The melodies, which were unfamiliar at initial exposure, evoked larger pupil dilation for vocal than for piano renditions. After sufficient time elapsed in the test phase to distinguish familiar from novel melodies, pupil dilation was larger for familiar than for novel melodies and for vocal than for piano melodies, which meant that it was greatest for melodies that were both vocal and familiar. The finding of greater pupil dilation for old melodies (i.e., heard once) than for new melodies indicates, for the first time, that pupil dilation can index melody recognition and, by implication, other auditory sequences of extended duration (i.e., 12 s or more). As expected, melody recognition unfolded more slowly than timbre recognition, in line with previous behavioral research (Dalla Bella et al., 2003).

Pupil dilation reflects arousal (e.g., Murphy et al., 2014), emotion (e.g., Sterpenich et al., 2006), attention (e.g., Gabay, Pertzov, & Henik, 2011), cognitive effort (e.g., Beatty, 1982), and stimulus salience (Liao et al., 2016). In the present context, greater pupil dilation for vocal than for piano melodies indexed listeners' heightened arousal for or engagement with vocal melodies, mediated, perhaps, by neuromodulatory mechanisms that enhance perceptual selectivity (Mather et al., 2015). Enhanced engagement with conspecific signals has been observed in various species (e.g., Braaten & Reynolds, 1999; Okabe et al., 2013).

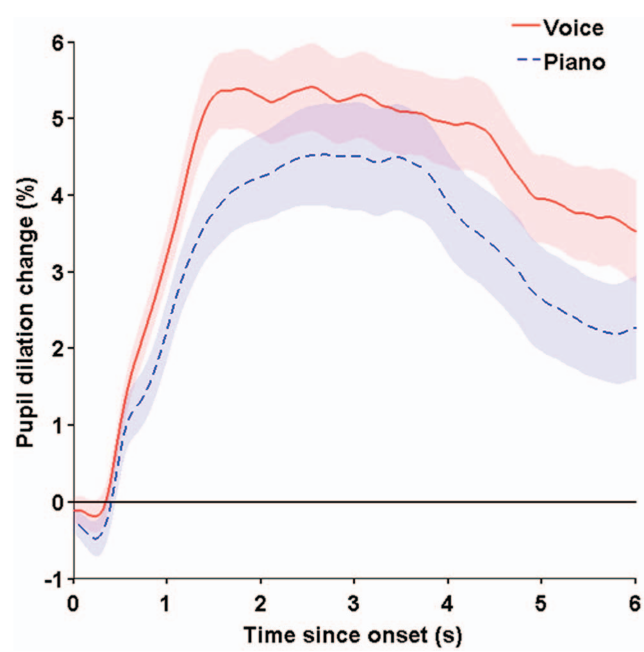

Figure 2. Average pupil dilation change (from baseline) during initial exposure as a function of timbre and time. Pupil dilation was significantly greater for vocal than for piano melodies across the six time bins. Shading represents *SEM*. See the online article for the color version of this figure.

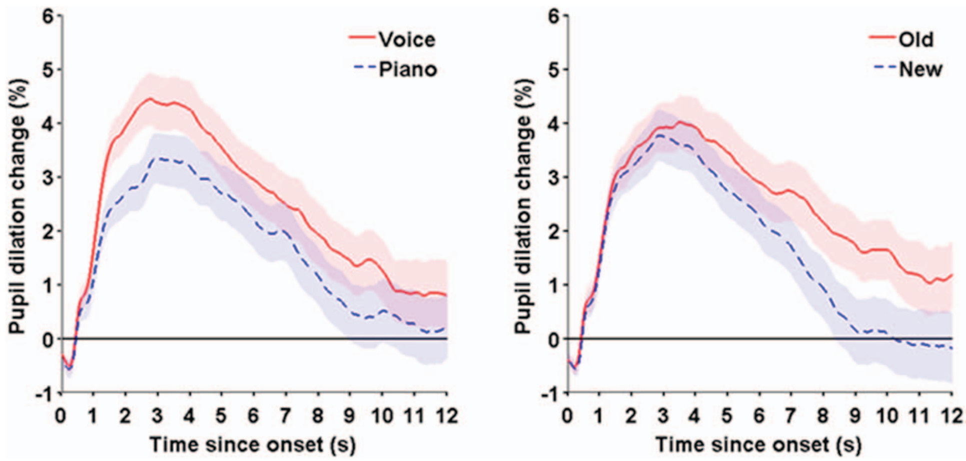

Figure 3. Average pupil dilation change (from baseline) during test phase as a function of timbre, exposure (old, new), and time. Pupil dilation was significantly greater for vocal than for piano melodies (collapsed across old/new, left panel) across time, and, after 6 s, for old than for new melodies (collapsed across timbre, right panel). Shading represents *SEM*. See the online article for the color version of this figure.

Songbird vocalizations are thought to have "incentive salience" because of the activation of neuromodulators that regulate the processing of rewarding stimuli (Maney, 2013). For human listeners, processing biases for conspecific signals may be regulated by networks that respond selectively to social signals. As noted, there is suggestive evidence that pupil dilation indexes activity in the LC-NE system (Aston-Jones & Cohen, 2005; Murphy et al., 2014).

Heightened engagement for vocal melodies is consistent with greater electrophysiological activation (e.g., Bruneau et al., 2013) and faster classification for vocal than for nonvocal sounds (e.g., Agus et al., 2012) and with higher subjective arousal ratings for vocal than for instrumental music (Loui, Bachorik, Li, & Schlaug, 2013). Although one might expect listeners to assign higher liking ratings to vocal melodies than to instrumental melodies, they did the reverse, as in previous research (Weiss et al., 2012, 2015a, 2015b), which is consistent with the dissociation of arousal from hedonic evaluations (Berridge, Robinson, & Aldridge, 2009; Bradley et al., 2008). Diminished liking of the present vocal melodies may stem from the repetitive syllabic content (*la la*), which compromised the aesthetic value of vocal stimuli without compromising their salience and memorability. More pleasing vocal renditions, such as those involving foreign lyrics or even humming, might be more memorable than the present renditions with repetitive syllables. In any event, we contend that vocal melodies, similar to emotional pictures and words, are highly salient for human observers and that the salience of vocal melodies underlies the pupil dilation effect as well as the memory advantage (Mather et al., 2015). Therefore, we would expect greater pupil dilation for more expressive performances of vocal melodies.

The demands of the present task, such as the fixed head position and instructions to minimize blinking, detracted from the usual music listening experience, with potential consequences for arousal, engagement, or memory. Unlike typical resting rates of 17 blinks per minute (Bentivoglio et al., 1997), the mean blink rate over 12 s of each trial was 1.24 (SD = 1.99), corresponding to 6.2 blinks per minute. The current blink rate is closer to blink rates during tasks such as reading that require sustained visual focus or cognitive effort (M = 4.5 blinks per minute; Bentivoglio et al., 1997).

Greater pupil dilation for vocal melodies than for piano melodies at initial exposure provides insight into the mechanisms underlying the subsequent recognition advantage, specifically greater arousal for vocal than for instrumental melodies. The implications of differential arousal on attention could be assessed by examining performance on a concurrent cognitive task during exposure to vocal and instrumental melodies. In any case, the present findings add weight to the accumulating evidence that vocal music is special for human listeners.

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