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Pupil Dilation Patterns Spontaneously Synchronize Across Individuals During Shared Attention

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Human social behavior relies on the coupling of minds. Here we show that patterns of pupil dilations reveal mental coupling between speakers and listeners. Speakers were videotaped and eye-tracked as they discussed positive and negative autobiographical memories. An independent group of listeners were then eye-tracked while they watched these videos. As pupillary dilations reflect the dynamics of conscious attention, we computed the morphological similarity of speaker-listener pupillary time-series data as a metric of shared attention. The emotional salience of each narrative was also assessed, dynamically, by independent raters. Collective pupillary synchrony between speakers and listeners was greatest during the emotional peaks of a narrative, and decreased as narratives became less engaging. Individual differences in speaker expressivity and listener empathy revealed greatest synchrony in high expressive-high empathic dyads. Together, these findings suggest that pupillary synchrony is an implicit corollary of shared attention that can be used to track mental coupling in real time.

Keywords: pupillary synchrony, pupil diameter, shared attention, norepinephrine, dynamic time warping

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As social animals, we spend much of our lives mentally coupled. The ability to attend to the same information as another person enables communication and connection, the transfer of information, and the creation of shared experience. Despite its importance for human social behavior, we know very little about how people share attention. This gap in our knowledge is attributable in part to the difficulty of catching it in the act. Here we test whether pupillary dilations provide a temporally sensitive and honest signal of shared attention. Specifically, we test whether pupillary dilations of speakers and listeners—both in dyads and across large groups of listeners—synchronize during moments of shared attention, revealing when a listener "tunes in" to what is being said.

The idea that synchrony is associated with shared mental states has been supported by several lines of research (see Wheatley, Kang, Parkinson, & Looser, 2012 for a review). We nonconsciously mirror individuals in our environments, and this mirroring becomes stronger with greater rapport (Bernieri & Rosenthal, 1991; Chartrand & Bargh, 1999). We feel more connected with those whose postures and vocal cadence (LaFrance, 1979), facial expressions (Dimberg, 1982), and even eyeblinks (Nakano, Yamamoto, Kitajo, Takahashi, & Kitazawa, 2009) match our own. Feelings of shared experience can also be reverse-engineered by inducing synchrony. Asking individuals to walk, tap, or wave synchronously increases feelings of connection and trust (e.g., Hove & Risen, 2009) and can lead to peculiar "self" versus "other" blurring, such as when synchronous stimulation leads to perceived ownership of another's face (Paladino, Mazzurega, Pavani, & Schubert, 2010) or even a rubber hand (Costantini & Haggard, 2007). Synchrony as a corollary of shared experience has also been observed at the emotional, physiological, and neural levels. Partners routinely synchronize their emotional dynamics to coordinate action and achieve mutual understanding (Butler, 2015); heart rates of fire-walkers synchronize with related, but not unrelated, spectators (Konvalinka et al., 2011); and neural synchrony emerges between individuals engaged in successful (but not unsuccessful) communication (Stephens, Silbert, & Hasson, 2010).

Here we investigate whether pupillary synchrony spontaneously emerges between two people when they share attention. Previous research has demonstrated that dynamic pupil dilation patterns provide a moment-by-moment attentional trace that can be used to identify what an individual is consciously attending (Kang & Wheatley, 2015). This attentional readout is possible because—under constant-light conditions—pupil diameter exhibits a tight association with the activity of the locus coeruleus (LC)–norepinephrine (NE) system (Rajkowski et al., 1993). The LC releases NE in response to salience, effecting changes in attention and arousal (Berridge & Waterhouse, 2003). The dynamic pupillary response therefore provides an involuntary and continuous readout of individuals' perceptions of salience (Hopstaken, van der

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Linden, Bakker, & Kompier, 2015; Laeng et al., 2012 for a review). In many ways, attention and arousal come part and parcel; focused attention is only possible during moderate arousal, when NE is tonically released at 3–5 Hz (Aston-Jones, Rajkowski, & Cohen, 1999). Within this window of moderate arousal, the present study focuses on the phasic (~20 Hz) bursts of NE released in response to attentional salience.

If the dynamic pupillary response reflects the ebb and flow of one's attention, pupillary synchrony should emerge when individuals share attention. Previous research suggests that we may mirror the pupil sizes we see in photographs of sad (but not happy) faces (Harrison et al., 2006) or trusted digital avatars (Kret et al., 2015). However, it is unclear whether these mirroring effects observed with static or interpolated images extend to dynamically coupled patterns of actual pupillary responses. We extend these findings here by measuring spontaneous pupillary synchronization patterns between speakers and listeners during both positively and negatively valenced communications.

To investigate pupillary synchrony, we adapted a paradigm by Zaki and colleagues (2008) in which "Speakers" who varied on expressivity were videotaped while they relayed emotional autobiographical memories for "Listeners" varying in affective empathy. In the original study, Speakers and Listeners independently watched these videos while using a slider to continuously rate how much affect the Speaker was feeling at the time. By comparing these dynamic behavioral traces, Zaki and colleagues (2008) determined that Listeners' empathic accuracy (cognitive empathy) could be predicted by their affective empathy only when paired with expressive Speakers. We adapt this paradigm here to test a different but related question: whether pupillary synchrony indexes shared attention between two or more minds.

First, we tested whether spontaneous pupillary synchrony emerges most in dyads likely to exhibit shared attention, that is, dyads comprising listeners who accurately take on others' perspectives (high cognitive empathy) and speakers who make their perspectives clear (high expressivity). We measured cognitive empathy (i.e., "mentalizing" or the ability to understand others' mental states) rather than affective empathy (i.e., sharing others' emotions), given the more robust association of cognitive empathy with accurate social understanding and effective communication (Davis, 1980; Kanske et al., 2016; Zaki et al., 2008). Second, we used reverse-correlation methods to compare patterns of *collective* synchrony that emerge across the entire population of speakers and listeners with continuous ratings of emotional salience collected from independent raters. These independent behavioral ratings were made in response to audio-only versions of speakers' narratives, allowing us to test whether periods of collective pupillary synchrony are motivated by narrative content independent of visual stimulation, emerging during the most emotionally charged portions of a narrative.

Method

Participants

Participants were recruited from Dartmouth College and compensated for their participation monetarily or with course credit. All participants were over 18 years of age, with normal or corrected-to-normal vision and audition. Written informed consent was obtained before the start of each phase. Participants who acted as Speakers additionally gave consent for the use of their recorded video narratives.

Speakers. Seventeen White female participants scoring in the outer quartiles of the Berkeley Expressivity Questionnaire (Gross, 2000) were recorded as Speakers for this study. Two high-expressive Speakers did not consent to the use of their videos as experimental stimuli, resulting in a total of 15 Speakers (9 high-expressive). Experimental stimuli were chosen from 8 of the remaining Speakers' video clips (4 high in expressivity and 4 low in expressivity).

Listeners. There were 137 participants who signed up to be Listeners during the recruiting window. Eleven participants did not complete the Interpersonal Reactivity Index (IRI; Davis, 1980); therefore, data for 126 participants (94 women) were used in the main analyses. A final analysis using reverse correlation methods did not depend on the IRI and therefore included data from all 137 participants.

Raters. Twenty-five participants (14 women) were independently recruited to make continuous ratings of emotional salience as they listened to audio-tracks of each narrative. Raters were not eye-tracked.

Eye-Tracking and Quality Control

Pupil diameter in both Speaker and Listener phases was recorded from the left eye at 120 Hz. Missing values were linearly interpolated. Trials requiring over 25% of the dilation data to be interpolated were discarded (see Kang & Wheatley, 2015). Resultant pupillary data was median filtered (order 5) and low-pass filtered (cutoff frequency 10 Hz) to remove spikes from the data, averaged into 100 ms bins, z-scored to account for individual differences in baseline pupil diameter and range of dilation, and detrended to correct for slow drift (see Smallwood et al., 2011; Wierda et al., 2012).

Behavioral Ratings

Raters' continuous ratings of narrative salience were collected at 10 Hz. Ratings were z-scored, detrended, and averaged across all Raters to produce a time-series of changing salience for each narrative.

Materials and Design

Pupillometry. Two eye-trackers were used during the course of this experiment. The ASL Eye-Trac 6 eye-tracker was used during the Speaker phase. For the Listener phase, 55 participants were recorded with ASL Eye-Trac 6 and 82 participants were recorded with SMI Red-m eye-tracker. Both eye-trackers sampled pupillary diameter at 120 Hz.

Measures of empathy and expressivity. The Berkeley Expressivity Questionnaire (Gross, 2000) was used to assess speakers' expressivity—how visibly they communicated their positive and negative emotional experiences to others (e.g., "Whenever I feel negative emotions, people can easily see exactly what I am feeling"). Listeners' cognitive empathy—their tendency to assume others' psychological viewpoints—was measured using the perspective-taking scale of the Interpersonal Reactivity Index (e.g., "I sometimes try to understand my friends better by imagining how things look from their perspective"; Davis, 1980).

Video stimuli. The experiment was split into Speaker and Listener phases, each using an independent group of participants. The Speaker phase yielded the video stimuli used in the Listener phase. Speakers were videotaped and eye-tracked as they related four autobiographical events. Following procedures used in Zaki et al. (2008), Speakers were told to prepare four of their most emotional memories (2 positive; 2 negative). As these would be recorded and used as stimuli, they were told to choose maximally emotional memories that they felt comfortable relating in a lab setting.

Speakers were seated approximately 30 inches away from the eye-tracker and video camera, with their heads between two wooden dividers (each divider approximately an inch from each ear). Dividers were used to limit large head movements that would obscure eye-tracking data. Before each narrative, each Speaker was taken through the following emotion elicitation paradigm (adapted from Zaki et al., 2008):

1. Each Speaker was given 5 minutes to write out their memory of the event. These events were titled and rated for overall valence and arousal on a 9-point Likert scale. They were told to include all details relevant to their emotional state during the original event.

2. Before videotaping, each Speaker was asked to spend 1 minute accessing and reliving their mindset during this event. When they felt that they had successfully attained the mental and emotional state experienced during the original event, Speakers described both the details of and their reactions to the event while videotaped and eye-tracked.

Eight videos (balanced for Speaker expressivity and narrative valence) were chosen as stimuli for the Listener phase of the experiment, such that positive and negative clips had comparable means and *SD*s for participants' subjective ratings of overall arousal. These videos detailed positive (e.g., falling in love) and negative (e.g., the death of a friend) events, and lasted an average of 2.85 min (average low-expressive video: 2.62 min; average high-expressive video: 3.09 min). As in Zaki et al. (2008), videos that were not scored as having an emotional intensity above the scale's midpoint were not used in the second phase of the study.

Listener phase. Listeners were seated approximately 30 inches away from the eye-tracker, and were told,

> "In this experiment, you will be watching videos of people telling stories about their lives. Some of these memories will be positive; some of them will be negative. Your only task during each video is to attend the Speaker, imagining that you're actually sitting across the table from her and listening to her talk."

Participants were instructed to keep their eyes on the screen during each video narrative to enable eye-tracking during each trial. After each video, Listeners rated how "likeable" or engaging each Speaker was on a 1–9 Likert scale (1 = *not at all likeable*, 9 = *extremely likeable*). See Figure 1 for a schematic of Speaker and Listener phases of the experiment.

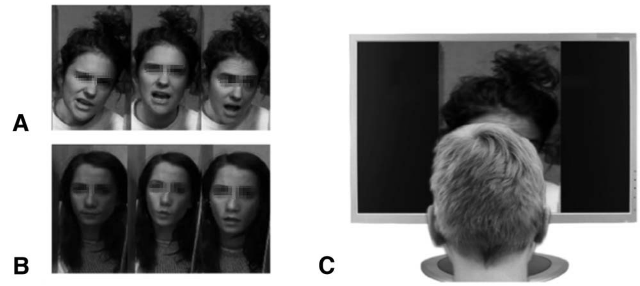

Figure 1. A schematic of the experimental paradigm. During the Speaker phase, high expressive (A) and low expressive (B) Speakers were videotaped and eye-tracked as they relayed emotional memories. In the Listener phase (C), participants were eye-tracked while they watched these videos.

Rater phase. Twenty-five independent raters listened to the audio tracks of all eight narratives. During each narrative, Raters made continuous ratings of narrative salience on a 1–9 scale (1 = *not at all interesting*, 9 = *maximally engaging*). "Narrative salience" was defined as "anything about the content or style of the story that changes how engaged you are with the narrative" regardless of whether this engagement was induced by semantic content or more sensory characteristics (e.g., if a sudden change in speakers' volume (re)captured participants' attention). These ratings were made using a physical slider bar (the Korg nanKONTROL USB Controller) and the Max/MSP program, and were captured at 10 Hz.

Data Analysis

Dynamic time warping. Dynamic time warping (DTW), a standard algorithm used to compare signals that may be offset in time (Berndt & Clifford, 1993), was used to measure pupillary synchrony between Speaker and Listener. Following the procedures outlined in Kang and Wheatley (2015), we computed the degree of preserved morphology (i.e., synchrony) between two pupillary time-courses by calculating their cosine similarity across 3-s windows with 1.5-s overlap. These parameters were chosen to ensure that each window contained a local but meaningful portion of the signal. DTW calculates the effort needed to align one signal to another and outputs this effort as a "cost value," such that the higher this value, the more *dissimilar* the two pupil dilation patterns (for details, see Kang & Wheatley, 2015).

Reverse correlation. To analyze the emergence of collective synchrony during Speakers' narratives, we used reverse correlation and cross correlation techniques to extract epochs of pupillary synchrony across all Listeners and compare these to behavioral ratings of narrative salience made by an independent group of raters. Reverse correlation has been used in neuroimaging studies to reveal what properties of a stimulus yield common fluctuations in hemodynamic response across individuals (see Hasson, Yang, Vallines, Heeger, & Rubin, 2008). For instance, Skipper and colleagues found that peaks in ventral premotor cortex activity corresponded to meaningful (but not to irrelevant) hand-gestures during storytelling (Skipper et al., 2006). We adapted these methods to the current design to extract a single time-course of pupillary synchrony across all Listeners for each narrative, and reverse correlate the moments of greatest synchrony to the portions of the narrative motivating them. We predicted that times of greatest collective synchrony (i.e., greatest shared attention) across all Listeners during a narrative would coincide with the most salient portions of Speakers' narratives (i.e., the peaks of the behavioral rating time-series).

Collective pupillary synchrony was calculated by parsing each pupillary time-series into 6s epochs, independently comparing each epoch across Speaker and Listener using previously described dynamic time warping procedures, and averaging the DTW costs associated with each epoch across all Listeners. This yielded a time-course displaying the peaks and valleys of collective synchrony over time. These were then correlated with the behavioral ratings of narrative salience (also averaged across 6 s epochs). Six second comparison windows were selected on the basis of data showing that the average duration of a spoken clause is 3 s, and that sentences are often comprised of at least two clauses (Hunt, 1970; Tauroza & Allison, 1990); this window of time is also in line with comparison windows used in prior research calculating the synchrony of dyads' behavioral ratings (Zaki et al., 2008). As idiosyncratic empathy was not a predictor for this collective analysis, data from all 137 Listeners were included.

Results

Dyadic Pupillary Synchrony

A linear mixed effects analysis of the relationship between Listeners' cognitive empathy, Speakers' expressivity, and pupil dilation synchrony was performed in R using the *lme4* package (Bates, Maechler, Bolker, & Walker, 2014). Listeners' mean-centered perspective-taking (PT) scores, Speakers' expressivity (high/low), and their interaction term were entered into the model as fixed effects. As random effects, we included random intercepts for subjects and videos. Data were log-transformed to correct for homoscedasticity. There was a significant interaction effect of Speaker expressivity and Listener empathy on pupillary synchrony, $F(1, 808.84) = 4.9225$, $p = .027$. The more readily Listeners adopted others' perspectives (i.e., measured by PT scores), the more their pupil dilation patterns synchronized with those of highly expressive Speakers. No such relationship existed with low-expressive Speakers (see Figures 2 and 3). There were no significant main effects. These results were replicated in an audio-only adaptation of the current paradigm (listeners heard but did not see the speakers), suggesting that pupillary synchrony is not dependent on visual mimicry or low level visual features (e.g., luminance; $F(1, 47) = 4.2037$, $p < .05$).

We also used linear mixed models to test the a priori prediction that shared attention would also yield greater subjective ratings of liking. Model comparisons conducted before significance testing revealed that a model containing Listeners' PT scores and Speakers' expressivity as fixed effects, and random intercepts for Listeners and videos best explained the variance in Listeners' liking ratings. A model additionally containing pupillary synchrony as a fixed effect did not explain significantly more variance, suggesting that shared attention alone is not a sufficient predictor of interpersonal liking. Statistical tests conducted on the optimal model revealed a significant effect of perspective-taking ($F(1, 119.11) = 8.89$, $p < .004$, $\beta = .05$) such that more empathic (vs. less empathic) Listeners tended to like Speakers more overall. There was also a marginal effect of the interaction of Listener empathy and Speaker expressivity ($F(1, 807.52) = 3.074$, $p = .079$, $\beta = .027$), suggesting that this increased liking by high empathy listeners was especially true when Speakers were highly expressive.

Reverse Correlation Analysis

To test whether collective synchrony emerged as a function of narrative content, we recruited an independent group of participants ("Raters") to continuously rate the emotional salience of

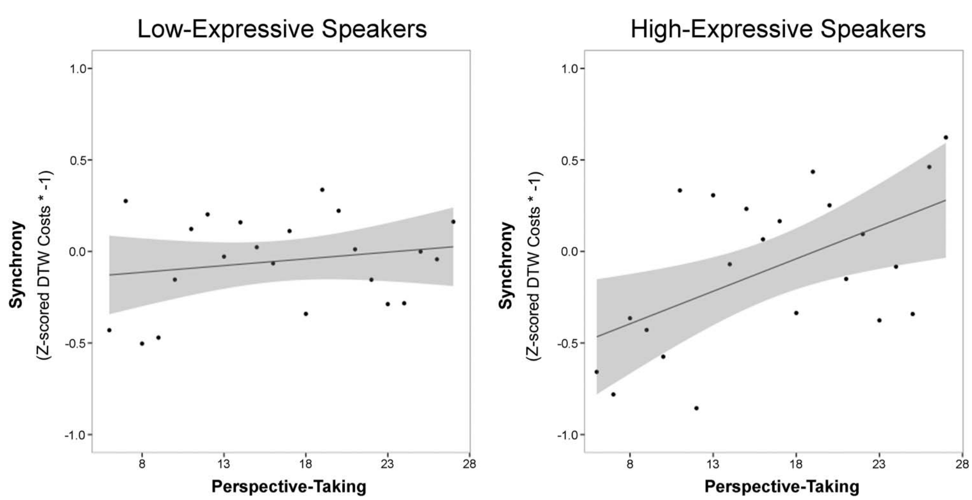

Figure 2. Pupillary synchrony increases as a function of empathy and expressivity. Listeners expressed synchronous pupil dilation with highly expressive (but not low expressive) Speakers as a function of cognitive empathy, $F(1, 808.84) = 4.9225$, $p = .027$. For visualization purposes, each data point in the above graphs represents the averaged synchrony score (z-scored Dynamic time warping [DTW] cost $^* -1$) across all Listeners scoring the indicated perspective-taking (PT) score (Interpersonal Reactivity Index [IRI]; Davis, 1980). PT scores ranged from 6–27 (available range 0–28). Error bars represent 1 *SEM*.

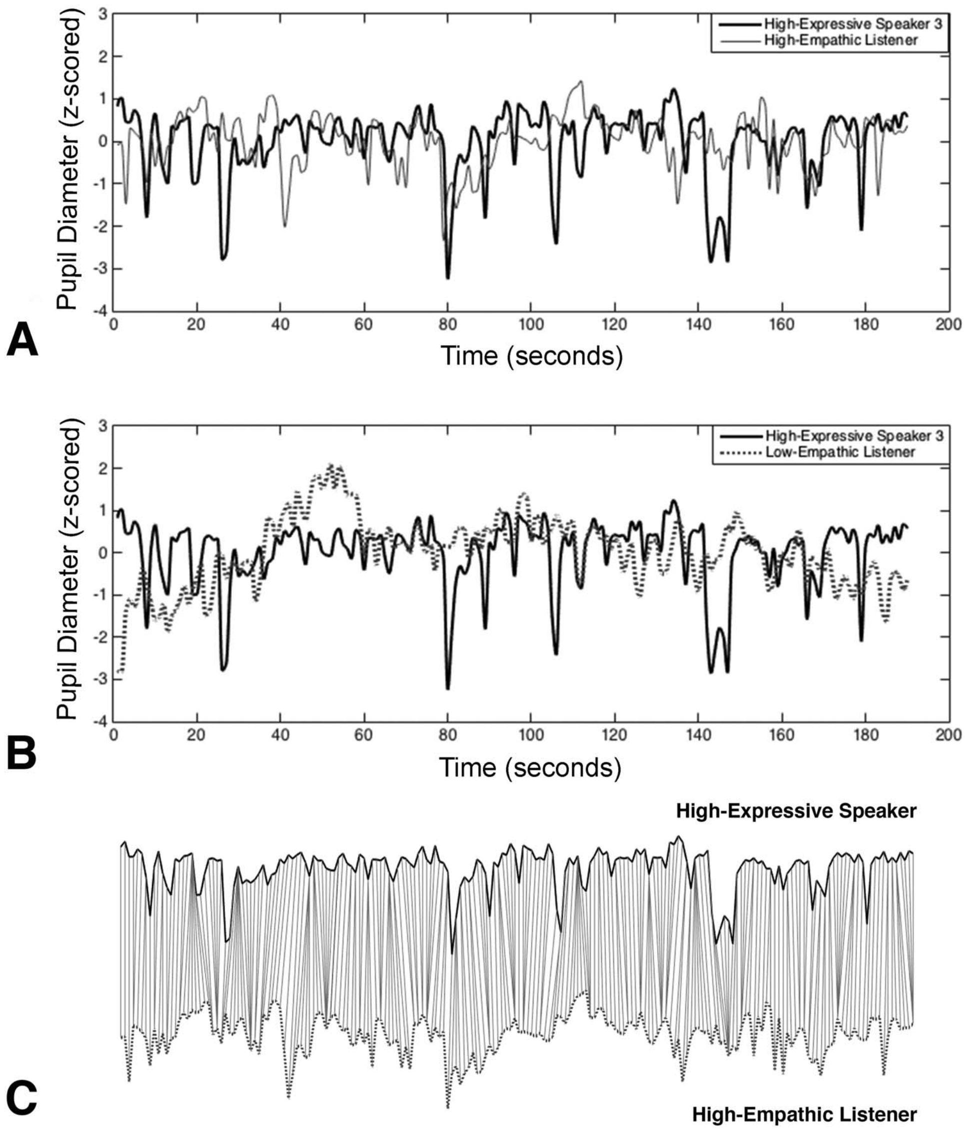

Figure 3. Pupil dilation patterns across a trial. Panels A and B show the pupil dilation dynamics of a single high-expressive Speaker with a representative high-empathic (Panel A) and a representative low-empathic (Panel B) Listener during an emotional narrative. Panel C visualizes the dynamic time warping of one pupillary signal to another.

Speakers' narratives using a physical dial. Their ratings were averaged to create time-series data representing the changing emotional salience of each narrative. We then computed how correlated these salience and synchrony time-series were for each narrative.

Correlation was used for this analysis for two reasons: first, DTW does not produce a standardized similarity metric. DTW computes the cost of aligning two signals (i.e., how *dissimilar* two signals are); however, as this cost value is directly influenced by the length of signal, it only takes on interpretive value when compared to the cost value of comparing another signal pair of identical length. As narrative lengths ranged from 56 seconds to over 5 minutes, DTW was not appropriate for computations of objective similarity across all narratives. Second, we hypothesized that the temporal dynamics across two populations of listeners (Listeners and Raters) would be consistent. We utilized cross-correlation analyses to adjust for expected time lag between pupillary responses (listeners) and motor responses (raters), and determined that the optimal lag was "1": behavioral responses occurred more slowly than physiological responses. Thus, across all narratives, synchrony and salience time-courses were correlated in the following manner: Point A on the synchrony time-course was correlated with Point A + 1 on the salience time-course, and so on.

For 7 out of 8 narratives, Listeners collectively synchronized their pupil dilations with Speakers' pupils during engaging (emotionally salient) portions of the narrative, and showed reduced collective synchrony during less-engaging portions of the narrative (see Figures 4 and 5). At lag 1, all significant correlations were moderate to strong (.3 to .9). The remaining narrative did not manifest a correlation between pupillary synchrony and emotional salience (Speaker 8). Although it is unclear why this is the case, we note that this Speaker scored more than 2 *SD*s below the mean for likability: 3.73 out of 9, $M = 6.16$, $SD = 1.4$.

Discussion

The notion that the eyes reveal the mind is ancient. Here we extend this age-old theory by demonstrating that the eyes can also reveal the coupling of two minds. Pupil dilations spontaneously and dynamically synchronize under conditions of shared attention.

Pupillary synchrony was greatest in dyads comprising expressive speakers and empathic listeners. Specifically, listeners' trait cognitive empathy predicted how much their pupils synchronized with the speakers', but only if the speaker was highly expressive. When speakers were less expressive, listener empathy had a diminished effect on synchrony, suggesting that listeners' empathic "literacy" is useful only to the degree that speakers provide a readable signal. However, even low-expressive/low-empathic dyads synchronized their pupil dilations sometimes. These moments of collective synchrony correlated with independent ratings of emotional salience, with synchrony peaking at the most affectively charged moments of a speaker's narrative. These findings were observed for both positively and negatively valenced stimuli.

By demonstrating the utility of pupillometry for studying mental coupling, this article opens up many important questions for future research. For example, *is pupillary synchrony between speakers and listeners dependent on a passive listener*? Would the effects seen here with unidirectional communication (e.g., speaker-listener, teacher-student) also hold for bidirectional communication typical in the give-and-take of social interaction? Also, what other information, beyond emotional salience, can be decoded from pupillary dilations? We recently demonstrated that pupillary dilation patterns can reveal which song a person is attending during a dichotic listening task (two songs simultaneously, one to each ear; Kang & Wheatley, 2015). In principle, a similar approach may be able to further decode the contents of joint attention.

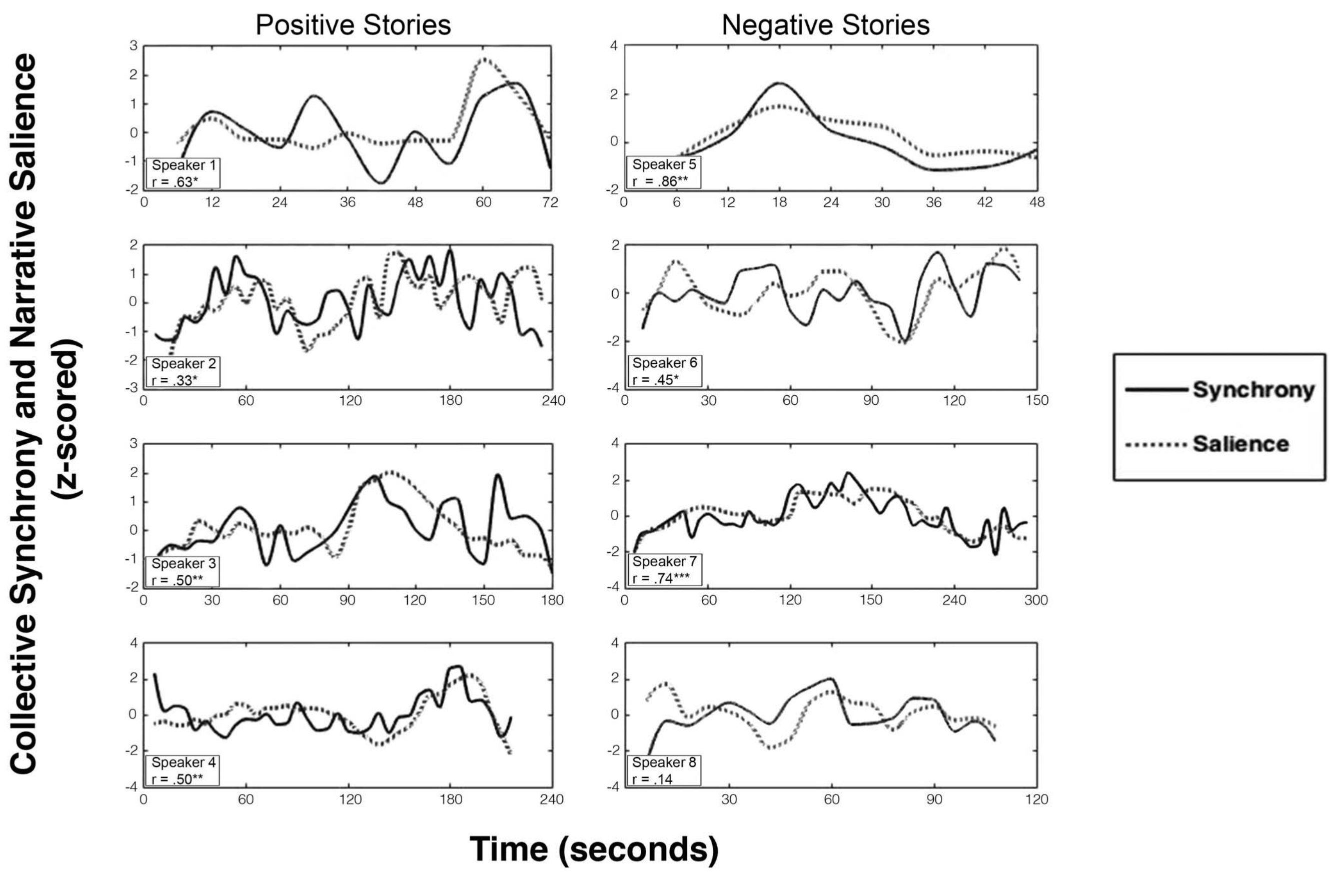

Figure 4. Collective synchrony across Listeners emerges with narrative salience. Collective pupillary synchrony was computed across 137 Listeners to create a time-series of collective attention for each of 8 narratives. These time-series were correlated with the time-series data representing changes in narrative salience at time lag = 1. Correlations are listed for each narrative (* $p < .05$; ** $p < .01$; *** $p < .001$). Seven of the 8 emotional narratives showed significant cross-correlations (r = .3 to .9). This suggests that attention is collectively shared during attentionally engaging portions of (engaging) Speakers' narratives.

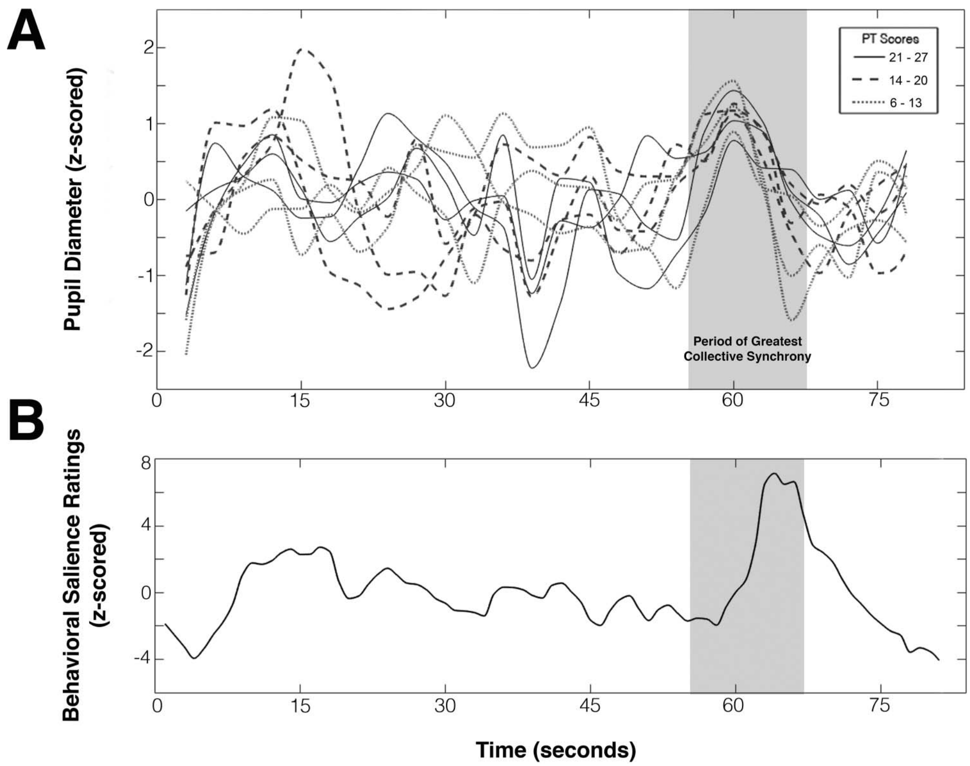

Figure 5. An illustration of collective pupillary synchronization during a Speaker's narrative. Panel A depicts the pupillary responses of 9 Listeners (3 from each of the following perspective-taking (PT) score ranges: 6–13; 14–20; 21–27 (range of collected scores: 6–27; range of possible scores: 0–28)) as they listened to the same Speaker narrative about a first kiss. Panel B shows the corresponding salience time-series created from independent behavior ratings across the same narrative. Reverse correlation revealed two consecutive 6-s periods of greatest collective synchrony (indicated by the shaded region above) that coincided with the climax of the narrative: "And then . . . it was silent for a few seconds, and he leaned over and actually did kiss me. And it was just so amazing because [clearing throat] I had really really interested in him [sic]." A temporal lag is seen between the implicit pupillary response and the (slower) behavioral rating.

However, as the pupillary response necessarily reflects the aggregate influence of many inputs across multiple timescales, from low-level sensory signals to high level cognitive interpretations, the signal may not be easily deconvolved (but see Weirda et al., 2012, for one approach). A simpler, if coarser, way to test whether factors are necessary for synchrony is to take particular cues away and see if synchrony still occurs. For example, we found that synchrony occurs in the absence of visual cues: collective synchrony was significantly coupled to salience ratings made by people who only listened to the stories, and dyadic synchrony emerged even when listeners only heard the speakers. This suggests that pupillary synchrony does not rely on visual mimicry or other visual inputs (luminance), but many questions remain.

Together, these findings reveal that spontaneous synchronization of pupil dilation patterns occurs when people share attention. Moreover, these findings illustrate the utility of pupillometry for observing, directly and dynamically, when and how minds couple in ways that support learning, communication, and connection.

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