Cognition 190 (2019) 93–98

Contents lists available at ScienceDirect

Cognition

journal homepage: www.elsevier.com/locate/cognit

Original Articles

Pupils say more than a thousand words: Pupil size reflects how observed actions are interpreted

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ARTICLE INFO

Keywords:
Social intention
Mindreading
Pupil size
Theory of mind
Kinematics

ABSTRACT

Humans attend to others' facial expressions and body language to better understand their emotions and predict goals and intentions. The eyes and its pupils reveal important social information. Because pupil size is beyond voluntary control yet reflective of a range of cognitive and affective processes, pupils in principal have the potential to convey whether others' actions are interpreted correctly or not. Here, we measured pupil size while participants observed video-clips showing reach-to-grasp arm movements. Expressors in the video-clips were playing a board game and moved a dowel to a new position. Participants' task was to decide whether the dowel was repositioned with the intention to be followed up by another move of the same expressor (personal intention) or whether the arm movement carried the implicit message that expressor's turn was over (social intention). Replicating earlier findings, results showed that participants recognized expressors' intentions on the basis of their arm kinematics. Results further showed that participants' pupil size was larger when observing actions reflecting personal compared to social intentions. Most interestingly, before participants indicated how they interpreted the observed actions by choosing to press one of two keys (corresponding to the personal or social intention), their pupils within a split second, had already given away how they interpreted the expressor's movement. In sum, this study underscores the importance of nonverbal behavior in helping social messages get across quickly. Revealing how actions are interpreted, pupils may provide additional feedback for effective social interactions.

1. Introduction

During social interactions, humans consciously and unconsciously communicate their emotions and intentions through a multitude of modalities. From this orchestra of bodily cues, the eyes represent one of the most critical sources of information (Innocenti, De Stefani, Bernardi, Campione, & Gentilucci, 2012; Van der Weiden, Veling, & Aarts, 2010), attracting special attention from the very first days of our life (Farroni, Csibra, Simion, & Johnson, 2002). In social interactions, eyes endorse a double function (Senju & Johnson, 2009). On the one hand, they can be used to transmit a range of social messages (Nakano & Kitazawa, 2010) and explicitly direct the attention of a partner during joint actions (Langton, Watt, & Bruce, 2000). On the other hand, eyes are the gate to the brain, where incoming information is processed and given meaning. The incoming information influences mental state, arousal, or emotion which is reflected in changes in pupil size (Bradley, Miccoli, Escrig, & Lang, 2008). Since pupil size is often visible for others, this provides immediate, genuine feedback to interaction partners (Kret, 2015). For example, it is known that pupil size reflects the understanding of others' emotional states (Bradley et al., 2008; Kret, Roelofs, Stekelenburg, & de Gelder, 2013; Kret, Stekelenburg, Roelofs, & De Gelder, 2013; Tamietto et al., 2009).

Zooming out from the eyes to the full body, research has shown that a vast diversity of information can be extracted from others' body movements during certain actions. For example, it has been shown that the weight of a carried object (Runeson & Frykholm, 1981), the direction of movement (Knoblich & Flach, 2001), the final position of an action (Martel, Bidet-Ildei, & Coello, 2011), and the type of action that is about to be realized (Marteniuk, MacKenzie, Jeannerod, Athenes, & Dugas, 1987) influences the early kinematics of the motor sequence. Moreover, explicit gestural communication (Sartori, Becchio, Bara, & Castiello, 2009), and communicative pointing movements (Cleret de Langavant et al., 2011; Oosterwijk et al., 2017) are influenced by the location of the addressee. Intriguingly, even for endorsing non-explicit

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https://doi.org/10.1016/j.cognition.2019.04.016
Received 18 November 2018; Received in revised form 18 April 2019; Accepted 19 April 2019
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communicative, social intentions (e.g. when passing an object to a partner), participants tend to unconsciously exaggerate the temporal (Ferri, Campione, Dalla Volta, Gianelli, & Gentilucci, 2010; Quesque & Coello, 2014; Quesque, Delevoye-Turrell, & Coello, 2015; Quesque, Lewkowicz, Delevoye-Turrell, & Coello, 2013; Quesque, Mignon, & Coello, 2017; Straulino, Scaravilli, & Castiello, 2016) as well as the spatial (Becchio, Sartori, Bulgheroni, & Castiello, 2008; Quesque & Coello, 2014; Quesque et al., 2013, 2015, 2017) parameters of their actions, compared to actions performed with a personal intention (that is, when others are not relevant for the accurate completion of the goal). Converging evidence suggests that these motor deviances, even if small, can be used by observers to understand the intentions that drive others' actions (Ciardo, Campanini, Merlo, Rubichi, & Iani, 2017; Lewkowicz, Quesque, Coello, & Delevoye-Turrell, 2015; Sartori, Becchio, & Castiello, 2011; Stapel, Hunnius, & Bekkering, 2012), especially when the contextual information is ambiguous (Koul, Soriano, Tversky, Becchio, & Cavallo, 2019). Some findings even support that they may spontaneously lead to the preparation of adaptive motor responses in the case of social intentions (Quesque et al., 2015). As a whole, this suggests that, through their motor expressions, others' social intentions can spontaneously elicit the preparation of complementary motor actions.

The research described above demonstrates that body language occupies an important role in human social interaction (de Gelder et al., 2010; Van den Stock, Hortensius, Sinke, Goebel, & De Gelder, 2015) and accumulating evidence suggests that naïve observers are able to discriminate subtle body cues to anticipate others' intentions (Ciardo et al., 2017; Koul et al., 2019; Lewkowicz et al., 2015; Sartori et al., 2011; Stapel et al., 2012; see also Cavallo, Koul, Ansuini, Capozzi, & Becchio, 2016 for evidences from a modelling approach). In order to anticipate others' goals, humans integrate information from the others' body movements and eye signals (Flanagan, Rotman, Reichelt, & Johansson, 2013; Rotman, Troje, Johansson, & Flanagan, 2006). The latter plays a fundamental role in this (Baron-Cohen, 1994) as is demonstrated by a study showing that humans attend to another's eyes rather than arms or hands, when predicting others' action goals (Letesson, Grade, & Edwards, 2015). To date, it is not known whether pupil size is affected by the observation of others' intentions reflected in subtle alterations of body movements. Knowing that pupil dilation reflects decisions even when not accessible to consciousness (Laeng, Sirois, & Gredebäck, 2012) and betray a person's choices before the overt execution of the actions (Einhäuser, Koch, & Carter, 2010), it could be postulated that pupil dilation reveals how others' intentions are interpreted. Through brief eye contact, it would then be possible to perceive how our intentions were interpreted. To investigate how pupils respond to others' motor actions driven by different social intentions is then of particular importance for the understanding of human's joint action abilities.

This was precisely the aim of the present study. Participants were presented with videos depicting arm movements of actors (who were naïve participants in an earlier study) reaching for an object and placing it at the center of a table, knowing that they would have to use it again, or knowing that their partner would, in a subsequent action. Participants were asked to categorize these video clips according to the intention (social or personal) of the actor. Meanwhile, their pupil sizes were being recorded. Our aims and predictions are threefold. First, we investigate whether people can categorize social intentions from the kinematics of arm movements only, as is predicted based on previous literature (Ciardo et al., 2017; Lewkowicz et al., 2015; Sartori et al., 2011). Second, we predict that participants' pupils differentiate between the personal and social intentions endorsed by the actors in the video clips. Third, as pupils are known to reflect mental processes, we expect they will reflect *how* another's action is interpreted, which is sometimes correct, and sometimes not.

2. Materials and methods

2.1. Participants

In accordance with previous work on neurophysiological effects of partner's body cues (Harrison, Singer, Rotshtein, Dolan, & Critchley, 2006; Schrammel, Pannasch, Graupner, Mojzisch, & Velichkovsky, 2009), 40 young adult students (27 females, mean age = 22.12, *SD* = 2.73) participated in the study. All had normal or corrected-to-normal vision, were screened for history of neurological, psychiatric diseases or medication, and had no prior knowledge of the experimental goals. They gave informed consent before participating in the experimental session that lasted approximately 30 min. The protocol followed the ethical standards defined by the local IRB and conformed to the principles of the Declaration of Helsinki. One participant was discarded from the categorization analysis for having given no behavioral response on more than half of the trials. For the pupillometric analysis, three participants were discarded with overall more than 50% of missing data and three additional participants were partly excluded with no pupil data for one of the eyes due to technical problems. (Kret & de Dreu, 2017; Kret, Fischer, & de Dreu, 2015; Van Breen, De Dreu, & Kret, 2018).

2.2. Stimuli

The stimulus material consisted of 10 unique video clips showing movements of the right arm of a naïve, typical person, 'person A' (Lewkowicz et al., 2015). Whilst being videotaped, person A was sitting opposite to another individual, person B, and a board game was positioned in between them (see Fig. 1. for an illustration of the setup). In half of the videos, Person A reached for the wooden dowel in front of him and placed it at the center of the table with the implicit goal to use it himself again in a subsequent action (personal intention) or, in the other half of the videos, with the goal to switch turns and allow Person B to reposition the dowel (social intention). Hence, the video clips consisted of a sequential action of two motor elements, a reach-to-grasp phase and a transport phase, which in total lasted approximatively 1.5 s. The subsequent action was not shown in the video. The video clips were cut exactly one frame after the object was placed at the center of the table. They were compressed with FFdshow codec (MJPEG) to 30 frames per second and a screen resolution of 640 * 480 pixels. A total of 10 different videos were used (5 with motor actions driven by social intentions and 5 with motor actions driven by personal intentions). They were selected to respectively display the most stereotypical kinematics of social and personal intentions for reach-to-grasp movements, presenting the minimum of overlap across conditions concerning the maximum elevation of the hand (Becchio et al., 2008; Quesque & Coello, 2014; Quesque et al., 2013, 2015, 2017; Sartori et al., 2009; Straulino et al., 2016), maximum velocity (2011; Becchio et al., 2008; Ferri et al., 2010; Straulino et al. 2015, 2016), movement duration (Ferri et al., 2010, 2011; Quesque & Coello, 2014; Quesque et al., 2013, 2015, 2017; Straulino, Scaravilli, & Castiello, 2015, 2016), and reaction time (Quesque & Coello, 2014; Quesque et al., 2013, 2015, 2017; Straulino et al., 2015, 2016). Characteristics of the movement parameters for the two types of intentions are described in the supporting information (Table S1). Each video was presented 12 times, adding up to a total of 120 stimuli, which were presented in a randomized order.

2.3. Procedure

Upon arrival in the laboratory, participants gave their informed consent. Next, they were seated at a table in a dark and silent experimental room, facing a 19-in. computer screen on which different videos were being displayed (see Fig. 1 for an illustration). An SMI RED 500 remote eye tracker was placed beneath the screen, allowing the

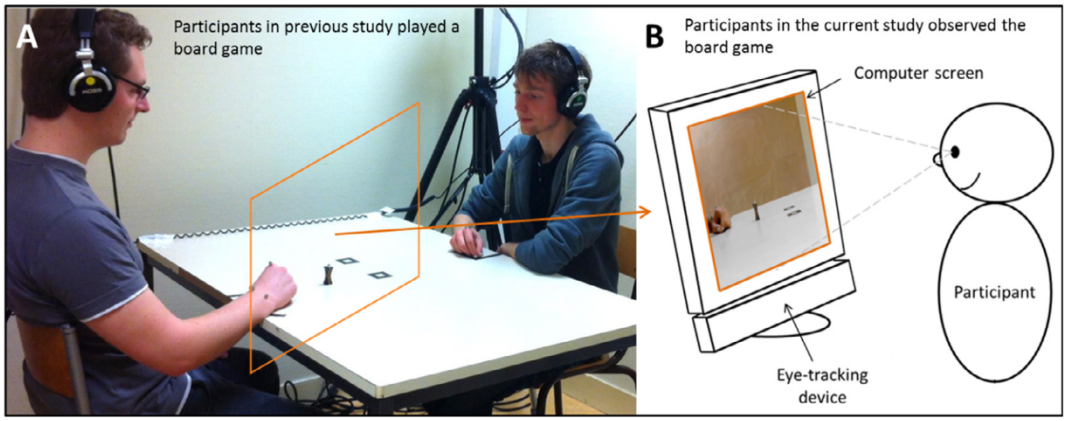

Fig. 1. (A) Picture of the initial paradigm from which the current video clips were recorded. Participants were seated on opposite sides of a table and were required to sequentially grasp and move a dowel to different locations on the table. At the beginning of each trial, one of the participants placed the dowel on the central location when receiving an auditory cue about who will be asked to perform the following action (himself or his partner). (B) Illustration of the current experimental setting. Participants were seated in front of a computer screen on which short video clips were displayed showing the reach-to-grasp movements. Their task was to categorize the video depending on the type of intention (personal or social) that drove the observed movements. During the whole experiment participants' pupil size was recorded by an eye-tracking device.

recording of the pupil size of participants. Two response keys were marked on an azerty USB keyboard (e.g. "left ctrl" for "social intention" and "right ctrl" for "personal intention", counterbalanced for half of the participants). Participants were instructed to watch and categorize the video clips according to the intention that they believed the actor endorsed. The instructions before categorization were displayed as follows: "You are going to see short videos of reaching and placing movements. For each video, you will have to decide if the dowel is placed for personal use or if it is placed for a partner to use it. You will respond by pressing one of the two response keys that are in front of you". Participants were instructed to categorize each movie clip as fast and as accurately as possible and to systematically respond even if they were unsure. No feedback was given during the experiment and the order of presentation of the video was randomized for each participant.

The videos were displayed on a black background on a computer screen using the *PsychToolbox* (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) for Matlab (Natick, MA). Each trial followed a precise sequence (see Fig. S1 for an illustration of the temporal set-up). The first frame of the video clip was displayed for 1500 ms followed by a black fixation cross in the middle of the screen for 500 ms, then the video clip was played and finally the last frame remained for 3000 ms. Participants were told to provide their response during this part of the sequence (the last frame interval). Finally, at the end of each trial, a resting period was inserted for 2000 ms where participants were encouraged to blink in order to moisturize their eyes.

2.4. Data processing

Behavioral data consisted of response times and accuracy scores. Response times (RT) were calculated as the time interval between the presentation of the last frame of the video and participant's key press. They were z-scored based on the mean and standard deviations (SD) of the RT per subject. Trials with z-scores above three SD and below minus three SD were excluded (32 trials; 0.6%). Concerning accuracy, the error in judging one type of stimulus (e.g. social intention video clips) corresponded with the correct judgment of the other type of stimulus (e.g. personal intention video clips). Consequently, participants' accuracy was expressed in terms of the total percentage of correct responses, which was compared to the level of chance (i.e. 50%, as there were two video types) with a one sample *t*-test (Bond & DePaulo, 2006).

Participants' pupil size was continuously sampled at 500 Hz and down-sampled to 10 Hz, i.e., 100-ms time slots over a response window of 3000 ms. We interpolated gaps smaller than 250 ms. Trials were excluded only if more than 50% of the data within that trial were missing (e.g., because the eye tracker lost the pupil). After applying this criterion and the cut-off for the reaction time described above, a total of 185 out of 4200 trials were excluded (0.05%) with 99 trials showing personal intention videos and 86 trials showing social intention videos. The maximum excluded trials per participant was 25 out of 120 trials with a median of 2 across participants. We smoothed the data with a 10th-order low-pass Butterworth filter (Cutoff frequency: 4 Hz). The average pupil size during the fixation cross (prior to the onset of the decision screen) served as a baseline and was subtracted from each subsequent sample.

2.5. Statistical analyses

To investigate the putative relationship between the pupillary response and the interpretation of the observed intentions based on arm movements, two types of multilevel linear model analyses were conducted. Multilevel analyses have been recommended for the analysis of physiological data including pupil size (Bagiella, Sloan, & Heitjan, 2000). Briefly, there are three major advantages to this procedure. First, it allows for missing data points. Although we only excluded trials with 50% or more missings (following standard procedures), some trials still had a few data points missing, which is normal with this type of data. Our multilevel analysis allowed for the inclusion of these trials. Second, this method allowed us to take into account both intrapersonal dependencies and interpersonal variances. Third, it is flexible to specify the outcome distribution of non-normally distributed data (such as binary decisions (e.g. accuracy) or skewed data (e.g. reaction time)).

The aim of the first analysis was to analyze participants' pupil size on trials where they had correctly interpreted the observed movements. Pupil size was predicted based on Video Type (personal or social). Furthermore, linear, quadratic and cubic orthogonal polynomials were added as both fixed and random slope effects to better represent the time course of the changes in pupil size and its subject-specific differences. 'Subject' was included as a random intercept effect. To capture time dependent correlations in pupil size, a first-order autoregressive (AR1) covariance matrix structure was used. Luminance of the last frame was added as a control variable, even though this did not have a significant effect. The analysis started with a full model including the two-way interactions with Video Type (social versus personal) and time (Linear, Quadratic, and Cubic polynomials) as fixed effects. Following standard model selection procedures, non-significant effects were excluded one by one, starting with the higher-order interactions. Non-

significant main effects or lower-order interactions were removed as long as no higher-order significant effect included these effects (for similar procedures, see Kret et al., 2015; Kret & de Dreu, 2017; Van Breen et al., 2018). The reduced final model is shown in the supporting information (Table S2). For exploratory purposes, the analysis was re-run with some additional factors including RT and time and their interactions with Video Type (Table S3).

The aim of the second analysis was to predict participant's decision (personal or social) based on his or her pupil size *prior* to the decision. A binary logistic multilevel linear model analysis was conducted with Decision as the dependent variable (coded: personal = 0, social = 1) and pupil size as the predictor. A time window of one second (10 data points) preceding the response was selected. Hence, the time interval was locked by the individual RT rather than the entire response window. 'Subject' was included as a random intercept effect. Again, in an exploratory analysis, we investigate potential modulations of the effects by RT.

3. Results

The key results of this study are threefold. First, replicating previous findings (Lewkowicz et al., 2015), we showed that participants can recognize other people's intentions from their arm movements ($t(3806) = 11.88$, $p < 0.001$, with a mean accuracy for social videos = 59.9%, and a mean accuracy for personal videos = 59.0%, see Fig. 2 for the individual distribution). Second, we investigated participants' pupillary responses during trials in which a correct decision had been made. In a multilevel mixed time-course analysis, pupil size was analyzed with Video Type (social or personal) as a fixed factor. In addition, to precisely model the curvature of participants' pupil size over time, Linear, Quadratic and Cubic orthogonal polynomials and their interaction with Video Type were included as fixed factors. The results showed a significant main effect of Video Type, indicating that participants' pupil size was larger following videos showing personal compared to social intentions ($F(1, 129837) = 4.76$, $p = .029$). Moreover, significant two-way interactions with Video Type and the linear, quadratic and cubic polynomials showed that the shape of the slope of participants pupil size over time differed depending on the Video Type (Linear polynomial * Video Type: $F(1, 129837) = 4.199$, $p = .04$; Quadratic polynomial * Video Type: $F(1, 129837) = 166.810$, $p < .001$; Cubic polynomial * Video Type: $F(1, 129837) = 82.978$, $p < .001$). Visual inspection of the graph (Fig. 3) showed that participants' pupil size differentiated between personal and social intentions, with a more pronounced and an earlier peak following the personal videos. In an exploratory analysis including RT, this differentiation was stronger in the fast, possibly more intuitive trials compared to the slow trials (Fig. S2).

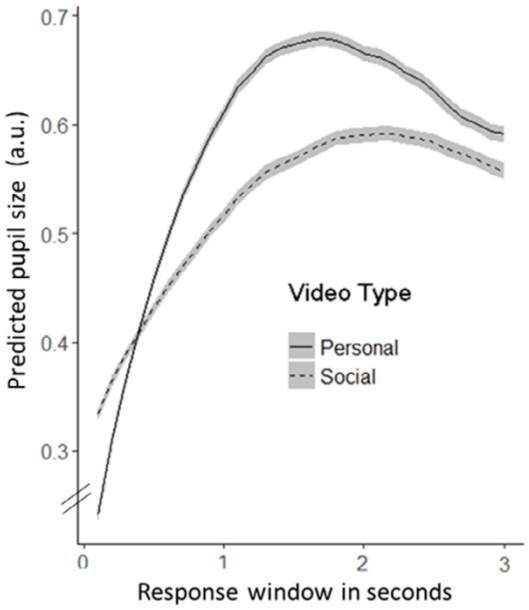

Fig. 3. Predicted mean pupil response (in arbitrary units) over time for personal (continuous lines) and social (dashed lines) videos with corresponding standard errors (grey shadow).

Third, in a logistic generalized linear model we investigated whether participants' interpretation of the observed videos (perceived as 'social' or 'personal' intention) could be predicted from their pupil sizes prior to indicating their interpretation by pressing the corresponding keys on a keyboard. Results showed that this was indeed the case ($F(1, 58201) = 55.623$, $p < 0.001$).

4. Discussion

The eyes are extremely important for social communication. With just a single glance, people can communicate their feelings and intentions and signal someone to either leave the room immediately, shut up, or give extra meaning to the verbal message at the end of a party to 'have another drink at my place'. By looking into someone's eyes, people check whether these messages come across and notice it immediately when they do not. What is it, within our eyes, that speaks out this message? We here propose that the pupil size may reflects how messages are interpreted. In the current study, participants watched videos of arm movements of person A playing a game with person B. In

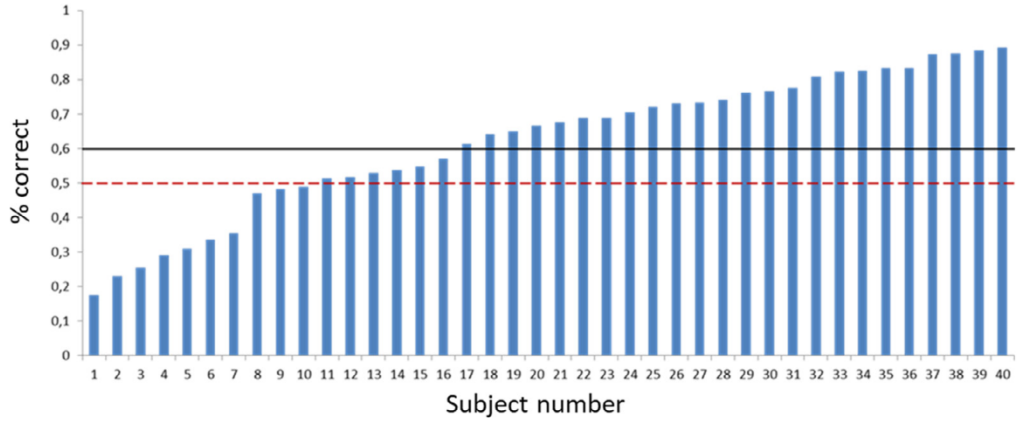

Fig. 2. Distribution of categorization scores for each participant. Participants' performances are displayed in ascending order. The horizontal black line represents the mean score and the dashed line represents the level of chance.

half of the videos, person A moved the dowel to a certain place on the board, knowing that he had to move it later on again to another location (personal intention movement). In the other half of the videos, person A moved the dowel to the same place, but knew that after this move, person B would take over to make the second movement (social intention movement). Without being aware of it, in the latter case, person A's arm movements were somewhat exaggerated, as if he wanted to communicate that it is the others' turn. Previous research has shown that naïve participants by just observing this arm movement can recognize the intention endorsed by this person (Lewkowicz et al., 2015). Replicating this finding, we here reveal that participants' pupils differentiate between social or personal motives. Participants' correct interpretation was reflected in their pupil sizes, but differentially so for videos showing personal or social intentions. Finally, even before participants explicitly indicated their decision whether the movements in a video contained social communicative cues or not, their pupils already gave away their decision, reflecting how the movement was interpreted.

The current study is the first in demonstrating that pupil size can reflect higher level social decision making. Previous research showed that a person's decision could be reflected in their pupil size (de Gee, Knapen, & Donner, 2014; Einhäuser et al., 2010; Fiedler & Glöckner, 2012). For example, pupil modulation has been found to be a marker of both the interpretation of ambiguous perceptual stimuli (de Gee et al., 2014; Einhäuser, Stout, Koch, & Carter, 2008; Hupé, Lamirel, & Lorenceau, 2009) and of the outcome of conscious reasoning (Einhäuser et al., 2010; Fiedler & Glöckner, 2012). It is also known that pupil size reacts to another person's emotional expressions (Bradley et al., 2008; Kret et al., 2015; Tamietto et al., 2009). In the present study we demonstrate that pupils are moreover sensitive to very subtle bodily cues betraying others' intentions. Changes in pupil size are regulated by the autonomic nervous system and are beyond our control, yet reflect ongoing cognitive effort, social interest and attention, surprise or uncertainty, as well as arousal paired with a range of emotions (Bradshaw, 1967; Hess, 1975; Lavín, San Martín, & Rosales Jubal, 2014). Because pupil changes are unconscious, they may constitute a discriminative information of others' decisions and allow partners to have a direct access to their private mental states during social interaction (see Becchio, Koul, Ansuini, Bertone, & Cavallo, 2018 for a discussion). Even if speculative, this interpretation is supported by two kinds of evidence. First, different studies demonstrated that eye-related cues are spontaneously considered when acting with a partner (De Stefani, Innocenti, Secchi, Papa, & Gentilucci, 2013; Ferri et al., 2011; Innocenti et al., 2012; Quesque & Coello, 2014). Second, recent works have shown that humans may use others' pupil changes to produce adaptive responses, without any training, when explicitly informed about their importance (Naber, Stoll, Einhäuser, & Carter, 2013) but also spontaneously in the absence of any instruction (Brambilla, Biella, & Kret, 2018; Kret & de Dreu, 2017; Kret et al., 2015; Van Breen et al., 2018). Whether potential partners may interpret high level social information as subtle as the one reported in the current study and adapt their behavior in response is however unknown and represent avenue for future research.

Why are pupils dilating more when interpreting a movement as personal? The precise pattern of these effects was not anticipated, and the interpretation remains therefore hypothetical. It is possible that this behavior reflects people's inner state of mind. It is known that the dilation of pupils is related to the arousing nature of stimuli (e.g. Bradshaw, 1967). Another explanation is that a certain pupillary behavior can have perceptual benefits (i.e. it makes one see better at small distances). Both interpretations would be congruent with spontaneous motor simulation frameworks (Gallese & Goldman, 1998; Rizzolatti & Craighero, 2004), recruiting their own motor system to interpret other's intention, participants would experience the drive for a consecutive action in the case of personal intention. A reversed pattern may however be expected when shifting from a third to a second person perspective (see Ciardo et al., 2017), in which the socially oriented actions of others could trigger the motor preparation of complementary response in the observer (e.g. Quesque et al., 2015). Here we demonstrated that pupil size was sensitive to others' intentions but to determine if pupil dilation is the cause or the consequence of participants' internal decisions (de Gee et al., 2014) remains an open question.

Although future investigations are necessary to understand the reasons that determine pupil size's sensitivity to others' intentions, the paradigm we developed here could constitute an implicit innovative task for the investigation of social cognition abilities which would not rely on explicit instructions. As suggested by the present work, the analysis of pupil size could represent a valuable and complementary way to test low levels of mind reading in non-verbal populations, where the use of eye behavior analysis recently reveals largely unsuspected abilities in preverbal children (Kovács, Téglás, & Endress, 2010; Onishi & Baillargeon, 2005; Southgate, Senju, & Csibra, 2007) and in non-human primates (Kret, Tomonaga, & Matsuzawa, 2014).

Acknowledgments

This work was supported by an IBRO-PERC InEurope Short Stay Grant and by Programme d'Investissements d'Avenir (PIA) and Agence Nationale pour la Recherche (grant ANR-11-EQPX-0023) to François Quesque and by the Netherlands Science Foundation (VENI # 016-155-082) to Mariska E. Kret. We thank Elio Sjak-Shie for his assistance in preprocessing the pupillometry data. The authors state no conflict of interest.

Appendix A. Supplementary materials

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cognition.2019.04.016.

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